Correlation of the angular dependence of spin-transfer torque and giant magneto-resistance in the limit of diffusive transport in spin valves

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Angular variation of giant magneto-resistance and spin-transfer torque in metallic spin-valve heterostructures is analyzed theoretically in the limit of diffusive transport. It is shown that the spin-transfer torque in asymmetric spin valves can vanish in non-collinear magnetic configurations, and such a non-standard behavior of the torque is generally associated with a non-monotonic angular dependence of the giant magneto-resistance, with a global minimum at a non-collinear magnetic configuration.

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where the corresponding electric field $E_0$ is taken far from the interface. Apart from this, $\Delta V^{\text{split}}_i = I_0 R^{\text{split}}_i$ for ferromagnetic films, $R^{\text{split}}_i = \frac{R_{i\sigma} + (1/R_{i\sigma})}{1}$, $R_{i\sigma} = R_{i\sigma} + d \rho_{\sigma} + R^{R}_{i\sigma}$ (for $\sigma = \uparrow, \downarrow$), with $\rho_{\sigma}$ being the corresponding spin dependent bulk resistivity, and $R_{i\sigma}$ and $R_{i\sigma}^{R}$ denoting the interfacial resistances (per unit square) associated with the left (right) interface of the $i$-th (ferromagnetic) film.

The total resistance of the system (per unit square) is $R = \Delta V/I_0$, while the magnetoresistance, $\Delta R(\theta) = R(\theta) - R(0)$, describes a change in the total system resistance when magnetic configuration varies from a non-collinear to parallel one. We note that what one needs to calculate are the $\Delta V^{\text{SI}}_i$ contributions only. It is convenient to define reduced magnetoresistance as

$$r(\theta) = \frac{R(\theta) - R_P}{R_{AP} - R_P}. \quad (2)$$

Several theoretical approaches have been proposed to describe the angular variation of GMR [8]. The explicit form for the reduced magnetoresistance, $r(\theta) = \sin^2(\theta/2)/[1 + \chi \cos^2(\theta/2)]$, has been extracted within the magneto-circuit theory [9] and diffusive approach [10]. In recent measurements on Py/Cu/Py valves [11] the parameter $\chi$ has been treated as a fitting parameter, and the $r(\theta)$ dependence was found to describe the experimental data relatively well. However, this formula breaks down for asymmetric spin valves, where a global minimum of the system resistance may appear at a non-collinear configuration [11].

Results: The minimum in resistance (and also in GMR) in a non-collinear configuration appears only in asymmetric spin valves. In the following we discuss the angular dependence of the STT and GMR in spin valves for positive current density. $I_0 > 0$ (electrons flow from right to left, or in other words current flows from the layer of thickness $d_1$ to the layer of thickness $d_2$). Figure 1(a) shows electric field profile in the Co($d_1$)/Cu($10$)/Co($8$) spin valve for $d_1 = 16 \text{ nm}$ sandwiched between semi-infinite Cu leads and for both parallel (P) and antiparallel (AP) magnetic configurations. The angular dependence of the corresponding voltage drops within the Co layers is shown in Fig.1(b). The voltage drop within the Co($16$) layer exhibits a very weak minimum for $\theta \approx \pi/3$. The minimum becomes much more pronounced for larger layer thickness, as shown in Fig.1(c) for $d_1 = 60 \text{ nm}$. Since the total voltage drop is a sum of all drops in the individual layers, the GMR can exhibit a minimum at a non-collinear configuration when the resistance decrease in the thick F layer overcomes the resistance increase in the thin F layer. The global minimum arises as a result of the spatial depletion of electrical field in the thick F layer, which is a consequence of spin accumulation discontinuity at the N/F interface controlled by the mixing conductances. The reduced GMR, $r(\theta)$, is shown in Fig.1(d) for both values of $d_1$. The non-monotonic behavior of the reduced GMR is more pronounced in spin valves that are more asymmetric, see Fig.1(e).

FIG. 1: (Color online) Transport characteristics of the biased Cu/Co($d_1$)/Cu($10$)/Co($8$)/Cu spin valve. (a) Spatial dependence of the electric field in the system for $d_1 = 16 \text{ nm}$ and for P and AP configurations. Angular dependence of the voltage drops in Co($d_1$) shown by dashed (blue) line and Co($8$) by solid (red) line for (b) $d_1 = 16 \text{ nm}$ and (c) $d_1 = 60 \text{ nm}$. (d) Angular dependence of the reduced magnetoresistance. (e) Reduced magnetoresistance as a function of $\theta$ and $d_1$. In parts (a), (b) and (c) the current density $I_0 = 10^3 \text{ A/cm}^2$ was assumed. The other parameters are as in Ref.[3].

In Figs 2(a)-(c), the diagrams present the regions of layer thicknesses, where the non-monotonic behavior of the reduced GMR can be observed (gray regions). For the Co/Cu/Co spin valves [Fig.2(a)] as well for the Py/Cu/Py ones [Fig.2(b)], the diagrams are symmetric with respect to $d_1 = d_2$, and the non-monotonic angular variation of the GMR (global minimum at a non-collinear configuration) can be noticed for spin valves with significantly different layer thicknesses. In Co/Cu/Py spin valves, where an additional asymmetry appears due to different magnetic materials, a non-monotonic angular variation of the GMR can be observed even for comparable layer thicknesses, see Fig.2(c). This is mainly due to strong asymmetry in spin diffusion lengths of Co and Py, but difference in the bulk as well as interface spin asymmetries of the Co and Py also contributes to the
The STT appears due to absorption of the transverse spin current component $j_{\perp}$ at the N/F interface \[12\], and can be calculated as
\[
\tau = \frac{\hbar}{2}(j_{\perp}^L - j_{\perp}^R),
\]
where the superscripts L and R denote the left and right interface, respectively, associated with the F layer. Dependence of the STT can also be expressed explicitly in terms of the mixing conductances and spin accumulation at the normal-metal side of the N/F interface \[3, 8\]. The STT consists generally of both in-plane and out-of-plane components. Since the latter component is much smaller than the former one (due to small imaginary part of the mixing conductances \[13\]), in the following discussion we will consider only the in-plane component. In asymmetric spin valves, the proper choice of magnetic materials and/or layer thicknesses can result in vanishing STT at a non-collinear magnetic configuration \[3\]. Such a non-standard STT destabilizes both collinear configurations for positive current and stabilizes both configurations for negative current \[3, 5\]. The former case is of particular interest as the non-standard torque leads to current-induced steady state oscillations in the absence of external magnetic field \[5, 6\]. In Fig 2(d) we show the angular dependence of STT in the Co(60)Cu(10)Co(8) spin valve exerted on the Co(60) (solid line) and Co(8) (dashed line). The STT acting on the Co(8) layer destabilizes P and stabilizes AP configuration, whereas the torque acting on the Co(60) vanishes at a non-collinear configuration and stabilizes both P and AP configurations. The torques in Fig 2(d) correspond to the system indicated by the dot in Fig 2(a). This point is below the critical line, given by $\partial\tau/\partial\theta|_{\theta=0} = 0$, which identifies the region where a non-standard STT acting on the Co($d_1$) layer appears. When the layer thicknesses are above the critical line, but still in the gray region, see the dot in Fig 2(b), the torque acting on the particular F layer vanishes only for the collinear configurations, as shown in Fig 2(e) for the Py(1)Cu(10)Py(6) spin valve, but reduced GMR still exhibits a global minimum for a non-collinear configuration. Since the critical lines are close to the boundary of the non-monotonic angular GMR behavior (gray regions), the non-standard STT is correlated with the non-monotonic angular variation of GMR.

At the critical angle $\theta_c$, where the torque $\tau$ vanishes, the transverse component of spin accumulation at the active interface disappears. In a general case, however, the angle $\theta_{\perp}$ between the spin moment of the F layer and spin accumulation vector at the normal-metal side of the N/F interface is nonzero. Angular dependence of the STT can be then expressed as a function of $\theta_{\perp}$ \[3\]. In Fig 3(a) and (b) the in-plane spin accumulation components at the normal-metal side (in the spacer layer) at the left and right interfaces are shown for the spin valves considered in Figs 2(d)-(f). The components are expressed in local coordinate frames, where $g_\perp$ points along magnetization in the left F layer whereas $g_\perp'$ along magnetization in the right F layer.

FIG. 2: (Color online) Diagrams illustrating presence of a global magnetoresistance minimum at non-collinear configurations - gray regions - and angular spin-transfer torque dependences. (a) Diagram for the Co($d_1$)Cu(10)Co($d_2$), (b) Py($d_1$)Cu(10)Py($d_2$), and (c) Co($d_1$)Cu(10)Py($d_2$) spin valve. The solid (red) and dashed (blue) lines denote critical thicknesses where $\partial\tau/\partial\theta|_{\theta=0} = 0$ for the torque exerted on the left F layer of thickness $d_1$ and right layer of thickness $d_2$, respectively. (d,e,f) Angular dependence of the spin-transfer torques acting on the left F layer of thickness $d_1$ – shown by solid (red) lines – and right F layer of thickness $d_2$ – shown by dashed (blue) lines – for systems corresponding to the dots in the left panel (a,b,c).
zation in the right F layer. The STT acting on Co(8) in the Co(8)Cu(10)Py(8) spin valve exhibits regular behavior. Spin accumulation in the P configuration is positive and has comparable amplitudes in the vicinity of both interfaces [see the dots on the dotted lines in Figs 3(a) and (b)] due to long spin-flip length in Cu \( (l_{sf} \approx 1 \mu m) \). When magnetization of the right layer rotates in the film plane, spin accumulation at the left interface roughly follows the net-spin of the Py(8) layer, and the angle \( \theta_g \) is a non-collinear configuration \( (\theta = \theta_c) \), for which the \( g_y' \) component also vanishes. At \( \theta = \theta_c \) one finds \( \theta_g = 0 \).

For the Co(60)Cu(10)Co(8) system, STT acting on the Co(60) layer shows a non-standard behavior which is qualitatively similar to that for the Py(8) layer in the Co(8)Cu(10)Py(8) spin valve. Angular variation of STT for the Py(1)Cu(10)Py(6) spin valve, shown in Fig. 2(e), vanishes regularly in P and AP configurations, and \( \theta_g \) is a monotonic function of \( \theta \).

Non-collinear configuration of the F layer magnetizations leads to discontinuities of the spin accumulation at the F/N interfaces [angle \( \theta_g \) in Figs 3(c) and (d)]. From this we deduce that if one takes the thickness of one of the F layers smaller than the corresponding spin diffusion length and thickness for the second F layer is larger than the appropriate spin diffusion length, then the spin accumulation is predominately determined by the later F layer. One finds then non-standard STT and non-monotonic GMR angular behavior. We have found that this behavior is mostly controlled by the mixing conductance of the interface between spacer layer and that F layer whose thickness is smaller than the corresponding spin diffusion length. For instance reducing the mixing conductance at the Co(8)/Cu(10) interface in the Co(8)Cu(10)Py(8) valve by about 50% lifts the non-standard STT and GMR behavior.

In conclusion, what stems from the above results is a need for further experimental investigations, and that Co/Cu/Py system is a good candidate to test the theoretical predictions. This also could answer the question whether the diffusive approach used to analyze CPP-GMR in collinear configurations is well justified. To arrive at more convincing conclusions one also should correlate the results on GMR with those on STT.

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![Figure 3: (Color online) Parametric plots of the in-plane spin accumulation components and angular dependences of the angle \( \theta_g \) between the spin accumulation and spin moments. (a) spin accumulation at the left (F/N) interface; (b) spin accumulation at the right (N/F) calculated at the normal metal side (N) in the vicinity of the active interfaces. The spin accumulation components are expressed in their local reference frames. The dashed (red) lines correspond to Co(60)Cu(10)Co(8); solid (black) lines to Py(1)Cu(10)Py(6); and dotted (blue) lines to Co(8)Cu(10)Py(8). The filled dots correspond to the parallel configuration of the layer magnetizations. Angular dependence of the \( \theta_g \) at the (c) left F/N and (d) right N/F interface.](image-url)