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Field-like spin torque in magnetic tunnel junctions

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Abstract.
We show that the exchange splitting asymmetry between the left and right ferromagnetic leads in non-collinear magnetic tunnel junctions (MTJ) tunes the bias behavior of the field-like spin torque, $T_{\perp}$. These results can be understood by our recently derived general expression, which relates the non-collinear $T_{\perp}$ to the algebraic sum of four independent non-equilibrium interlayer exchange couplings (IEC) solely in collinear configurations.

1. Introduction
In the recent years, there has been intense research effort in using the spin-transfer-torque effect (STT), originally predicted by Slonczewski [1] and Berger [2], to induce reversal or precession of ferromagnetic layers. This new effect of current-induced magnetization reversal (CIMR) in magnetic tunnel junctions (MTJ), has the potential to create a new generation of nonvolatile magnetic random access memories (STT-MRAM) and nanoscale current-tunable microwave sources and oscillators.

Slonczewski [1] has demonstrated that the interlayer exchange coupling (IEC) can be directly related to the field-like spin torque, $T_{\perp}$, which is perpendicular to the plane of the magnetizations of the left and right ferromagnetic (FM) leads. The bias behavior of $T_{\perp}$ has been studied both experimentally [3, 4, 5] and theoretically [6, 7, 8, 9]. However, the experimental results of the bias behavior of $T_{\perp}$ remains controversial, ranging from quadratic [3, 4] to linear [5]. Recently, we have demonstrated that the low-bias behavior of $T_{\perp}$ can be tuned with the asymmetry in band filling (BF) between the FM leads, which have the same exchange splitting, $\Delta$, thus reconciling the experimental findings [10]. The underlying mechanism for the bias behavior of $T_{\perp}$ is the interplay between four non-equilibrium IEC’s in collinear (FM or antiferromagnetic) configuration.

The purpose of this work is to investigate the effect of asymmetry in exchange splitting, $\Delta_L \neq \Delta_R$, between the FM leads on the bias behavior of the field-like torque in non-collinear MTJ. We demonstrate that each IEC between the spin channels $\sigma$ and $\sigma'$ of the left and right leads is independent of the others, thus allowing the control of each IEC by varying selectively...
the band filling of individual spin channels of the FM leads. This may be important in future CIMR applications.

2. Methodology
The MTJ consists of the left (L) and right (R) semi-infinite FM leads sandwiched by a 5-layer non-magnetic insulating barrier. The magnetization, \( \mathbf{M}_L \), of the right FM lead is along \( z \), while that of the left FM lead, \( \mathbf{M}_L \), is rotated by the angle \( \theta \) around the \( y \) axis with respect to \( \mathbf{M}_R \), shown in Fig. 1 of Ref. [10]. We employ the single-band tight binding model with the non-equilibrium Keldysh formalism to investigate the bias behavior of the MTJ. The nearest-neighbor (NN) spin-independent hopping matrix element, \( t = -0.4 \) eV, in all regions, the on-site energy of the barrier, \( \varepsilon_B = 5.4 \) eV, the Fermi energy \( E_F = 0 \) eV, and the on-site energy levels of the majority and minority bands of the left FM lead are, \( \varepsilon^\parallel_L = 0.6 \) eV and \( \varepsilon^\perp_L = 1.2 \) eV, respectively, resulting in an exchange splitting \( \Delta_L = \varepsilon^\perp_L - \varepsilon^\parallel_L = 0.6 \) eV. The choice of the parameters provides a realistic choice for systems based on magnetic transition metals and their alloys[10]. As shown in Fig. 1(a), the MTJ asymmetry is introduced by rigidly shifting the minority-spin on-site energies, \( \varepsilon^\perp_R \), of the right lead while keeping fixed \( \varepsilon^\parallel_R = \varepsilon^\parallel_L = 0.6 \) eV. This in turn changes both the band filling of the minority band and the exchange splitting of the right lead, \( \Delta_R \).

We have demonstrated that the bias dependence of the net \( T_\perp \), can be simply expressed as the sum of four non-equilibrium IEC’s solely in the FM configuration [10],

\[
T_\perp(\theta) = -[J^\parallel_{FM} + J^\perp_{FM} - J^\parallel_{FM} - J^\perp_{FM}] \times \sin \theta,
\]

where the non-equilibrium IEC, \( J^{\sigma\sigma'}_{FM} \), between the \( \sigma \)- and \( \sigma' \)-spin states in the left and right leads, respectively, in the FM configuration are given by

\[
-J^{\sigma\sigma'}_{FM} \approx \frac{t^4}{8\pi^3} \int g_{ba}g_{ab} \left[ f_L(E)Im\{g^{\sigma\sigma'}_{L}\} Re\{g^{\sigma\sigma'}_{R}\} + f_R(E-eV)Re\{g^{\sigma\sigma'}_{L}\} Im\{g^{\sigma\sigma'}_{R}\} \right] d\mathbf{k}_\parallel dE.
\]

Here, \( g_{ab}[g_{ba}] \) is the Green’s function of the isolated barrier which is real, and the subscripts \( a \) and \( b \) denote the first and last sites inside the barrier. \( g^{\sigma\sigma'}_{L(R)} \) is the retarded surface Green’s function for the isolated semi-infinite left (right) FM lead with \( (\sigma, \sigma') = (\uparrow, \downarrow) \). \( f_L(E) \) and \( f_R(E-eV) \) are the Fermi-Dirac distribution functions of the left and right FM leads, respectively, \( V \) is the external bias, and \( \mathbf{k}_\parallel \) is the transverse component of the wave vector.

3. Results and discussion
In Fig. 1(b) we present the bias behavior of \( T_\perp \) for various values of the exchange splitting of the right FM lead, \( \Delta_R \). When \( \Delta_R > \Delta_L \), i.e. the minority-spin energy band (or BF) in the right FM lead is higher (lower) than that of the left FM lead [Fig. 1(a)], the low-bias maximum of \( T_\perp \) shifts in the negative bias region. In the opposite case, \( \Delta_R < \Delta_L \), the low-bias maximum of \( T_\perp \) shifts to the positive bias region. This behavior is similar to previously reported theoretical results [11].

Since Eq. (1) shows that the bias behavior of \( T_\perp \) can be decomposed into four non-equilibrium IEC, \( J^{\sigma\sigma'}_{FM} \) with \( (\sigma, \sigma') = (\uparrow, \downarrow) \), solely in the FM configuration, we display in Fig. 2 the bias dependence of the four \( J^{\sigma\sigma'}_{FM} \) for \( \Delta_R = 0.6 \) eV (symmetric MTJ) and \( \Delta_R = 1.2 \) eV. In the symmetric case, the bias behavior of the \( -J^{\parallel\perp}_{FM} \) and \( -J^{\parallel\perp}_{FM} \) is symmetric with respect to zero bias, due to the fact that that both the majority- and minority-spin energy bands of the left and right FM leads are the same. On the other hand, the different BF of the left spin-\( \uparrow \) (\( \downarrow \)) band and the
Figure 1. (a) Schematic of asymmetric MTJ, where the black and gray horizontal solid lines represent the bottom of the majority- and minority-spin energy bands. Upon rotation of $M_L$ along $M_R$, the majority- (minority-) energy bands of the left lead acquire minority- (majority-) energy contributions. The exchange splitting of the left (right) FM leads are denoted by $\Delta_L$($\Delta_R$). (b) $T_\perp$ as a function of bias for various values of $\Delta_R$.

right spin-$\downarrow$ ($-\uparrow$) band gives rise to the asymmetric bias behavior of $-J^{\uparrow\downarrow}_{FM}$. However, their algebraic sum, $T_\perp$, retains its symmetric bias behavior, because the majority- and minority-spin BF are the same for both left and right FM leads.

For the asymmetric case, since we shift only the minority-spin band of the right FM lead, the bias behaviors of $-J^{\uparrow\downarrow}_{FM}$ and $-J^{\downarrow\uparrow}_{FM}$ remain the same. On the other hand, the bias behavior of $-J^{\uparrow\downarrow}_{FM}$ and $-J^{\downarrow\uparrow}_{FM}$ is shifted towards the negative bias region, because of the BF asymmetry between the majority-spin (minority-spin) band of the left and the minority-spin (majority-spin) band of the right lead increases with increasing $\Delta_R$. Consequently, their algebraic sum shown leads to the asymmetric bias behavior of $T_\perp$ shown in Fig. 1(b).

These results reveal that the four $J^{\sigma\sigma'}_{FM}$ in Eq. (1) are independent of each other and they only depend on the BF of $\sigma$-spin band of the left lead and the $\sigma'$-spin band of the right lead, regardless of the other three IEC. Therefore, the bias behavior of $T_\perp$ can be controlled by tuning the BF of the individual spin-channels of the left and right FM leads. Finally, since the antiferromagnetic (AF) configuration can be obtained by exchanging the majority-spin and minority-spin bands of the left lead, we have that $J^{\uparrow\downarrow}_{FM} = J^{\downarrow\uparrow}_{AF}$, $J^{\uparrow\downarrow}_{FM} = J^{\downarrow\uparrow}_{AF}$, $J^{\uparrow\downarrow}_{FM} = J^{\downarrow\uparrow}_{AF}$, and $J^{\uparrow\downarrow}_{FM} = J^{\downarrow\uparrow}_{AF}$. Thus, Eq. (1) also can be recast in the form of the algebraic sum of $J^{\sigma\sigma'}_{AF}$ in the AF configuration.

4. Conclusion
We demonstrate that the bias behavior of the field-like torque, $T_\perp$, in non-collinear MTJ can be controlled via the exchange splitting asymmetry between the ferromagnetic leads. The shift of the low-bias maximum of $T_\perp$ can be understood by the interplay of four independent non-equilibrium IEC’s, $J^{\sigma\sigma'}_{FM}$ or $J^{\sigma\sigma'}_{AF}$, in collinear configurations. Each IEC depends solely on the BF of the $\sigma$-spin and $\sigma'$-spin states in the left and right FM leads, respectively.

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Figure 2. Bias dependence of the four IEC’s, $-J_{\sigma\sigma'}_{FM}$ where $(\sigma, \sigma') = (\uparrow, \downarrow)$, in the FM configuration for (a)$\Delta_R=0.6$eV and (b)$\Delta_R=1.2$eV.

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