Current-driven magnetization switching and dynamic spin reorientation transition in magnetic tunnel junctions

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Abstract. We present theoretical results on electrically induced magnetization dynamics in CoFeB/MgO/CoFeB tunnel junctions connected to a constant-current source. Our calculations take into account both the spin-transfer torque (STT) created by a spin-polarized current and a voltage-controlled magnetic anisotropy (VCMA) associated with the CoFeB|MgO interface. It is shown that the current-driven spin dynamics in an ultrathin free layer of such junction is not limited by the magnetization precession and switching, but also can have the form of a dynamic spin reorientation transition, which is caused by the combined action of STT and VCMA and gives rise to a steady precessional state. Critical current densities necessary for the appearance of different types of magnetic dynamics are calculated as functions of the free-layer thickness and in-plane aspect ratio. The spin current pumped into a normal-metal overlayer by the tunnel junction with the precessing magnetization is also evaluated.

Magnetic tunnel junctions (MTJs) are suitable for various device applications, including read heads of hard-disk drives [1], non-volatile magnetoresistive memory [2, 3], and frequency-tunable microwave sources and detectors [4, 5]. A dynamical response of the junction’s free magnetic layer to an external stimulus can have the form of a steady magnetization precession, spin reorientation transition (SRT), or magnetization reversal. An energy efficient technique for the generation of magnetic dynamics in MTJs is based on passing a spin-polarized current through the free layer (FL), which exerts a spin-transfer torque (STT) on the magnetization [6].

In this work, we theoretically investigated the current-driven magnetization dynamics in CoFeB/MgO/CoFeB tunnel junctions, which are distinguished by the presence of a voltage-controlled magnetic anisotropy (VCMA) associated with the CoFeB|MgO interface [4]. Our study is focused on MTJs comprising an ultrathin FL with a perpendicular magnetic anisotropy and an in-plane magnetized pinned layer (PL) (see figure. 1). Such magnetic configuration enhances the STT acting on the FL, which should reduce the density of a direct current necessary to induce dynamical spin phenomena in the MTJ.

The magnetization dynamics in the CoFeB FL with a rectangular shape and nanoscale in-plane dimensions $L_1 > L_2$ was determined in the macrospin approximation via numerical integration of the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation [7] accounting for both STT and VCMA [8]. We considered MTJs connected to a constant-current source, which keeps the current fixed irrespective of the MTJ conductance. Accordingly, the tunnel current density $J$ was pre-set during each simulation. In contrast, the voltage drop $V = J/G$ across the MgO barrier of thickness $t_b$ was treated as a variable quantity since the MTJ conductance $G$ depends
on the angle between the unit vectors \( \mathbf{m} \) and \( \mathbf{m}_{\text{pin}} \), defining the magnetization directions in FL and PL, respectively [6]. The LLGS equation was solved in the form

\[
\frac{d\mathbf{m}}{dt} = -\gamma \mu_0 \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \frac{\tau_{\text{STT}}}{M_s} \mathbf{m} \times (\mathbf{m} \times \mathbf{m}_{\text{pin}}),
\]

where \( \gamma > 0 \) is the electron’s gyromagnetic ratio, \( \mu_0 \) is the vacuum permeability, \( \alpha \) is the Gilbert damping parameter, \( \mathbf{H}_{\text{eff}} \) is the effective field acting on the FL magnetization \( \mathbf{M} = M_s \mathbf{m} \), and the last term describes the STT. The factor \( \tau_{\text{STT}} \) in Eq. (1) was calculated as \( \tau_{\text{STT}} = (\gamma \hbar/2e)(J/t_f)\eta/(1 + \eta^2 \mathbf{m} \cdot \mathbf{m}_{\text{pin}}) \), where \( e \) is the elementary (positive) charge, \( \hbar \) is the reduced Planck constant, \( t_f \) is the FL thickness, \( \eta = \sqrt{(G_p - G_{\text{AP}})/(G_p + G_{\text{AP}})} \), and \( G_p \) and \( G_{\text{AP}} \) are the MTJ conductances per unit area in the states with parallel and antiparallel electrode magnetizations, respectively [6]. The effective field is defined by the relation \( \mathbf{H}_{\text{eff}} = -(\mu_0 M_s)^{-1} \partial F/\partial \mathbf{m} \), where \( F(\mathbf{m}) \) is the FL Helmholtz free energy density. For the considered homogeneously magnetized unstrained CoFeB layer, the magnetization-dependent part \( \Delta F(\mathbf{m}) \) of the effective volumetric energy density can be expressed by the polynomial

\[
\Delta F = K_1 (m_1^2 m_2^2 + m_1^2 m_3^2 + m_2^2 m_3^2) + K_2 m_1^2 m_2^2 m_3^2 + \frac{K_s}{t_f} m_3^2 + \frac{1}{2} \mu_0 M_s^2 (N_{11} m_1^2 + 2N_{12} m_1 m_2 + N_{22} m_2^2 + N_{33} m_3^2) - \mu_0 M_s (H_1^{\text{int}} m_1 + H_2^{\text{int}} m_2 + H_3^{\text{int}} m_3),
\]

where \( K_1 \) and \( K_2 \) are the coefficients defining the cubic magneto-crystalline anisotropy, \( K_s \) characterizes the total specific energy of two interfaces, and \( N_{ij} \) are the demagnetizing factors [9]. The interaction field \( \mathbf{H}_{\text{int}} \) involved in Eq. (2) is the sum of the external field \( \mathbf{H} \) and the effective field \( \mathbf{H}_{\text{iec}} = U_{\text{iec}}(\mu_0 M_s t_f)^{-1} \mathbf{m}_\text{pin} \) resulting from the energy of the interlayer exchange coupling \( U_{\text{iec}} \approx 5.78 \exp(-7.43 \times 10^9 t_b) \) mJ m\(^{-2}\) [10] with the PL. The VCMA associated with the CoFeB/MgO interface was taken into account by setting \( K_s = K_0 + k_s J/(G t_b) \), where \( k_s = \partial K_s/\partial E_3 \) is the sensitivity of \( K_s \) to the electric field \( E_3 = V t_b^{-1} \) in the MgO barrier.

Numerical calculations have been performed with the aid of the projective Euler scheme for the Co\textsubscript{20}Fe\textsubscript{60}B\textsubscript{20}/MgO/Co\textsubscript{20}Fe\textsubscript{60}B\textsubscript{20} junctions. The FL thickness was varied just below the
critical value \(t^*\), at which the FL acquires a perpendicular magnetic anisotropy [11]. In contrast, the PL thickness \(t_p\) was taken to be well above \(t^*\) so that the pinned magnetization \(\mathbf{M}_{\text{pin}}\) was assumed to be oriented along the in-plane \(x_2\) axis (figure 1). The external magnetic field \(\mathbf{H}\) was either directed along the pinned magnetization \((H_1 = H_3 = 0)\) or set to zero. Thus, the numerical solution of LLGS-equation was performed for the specific geometry, at which the external magnetic field is parallel to the pinned magnetization and to the short side \(L_2\) of the rectangular PL.

The saturation magnetization \(M_s = 1.13 \times 10^6\) A m\(^{-1}\) [12] and the intrinsic damping parameter \(\alpha_0 = 0.01\) [11] were assigned to the FL. The magnetocrystalline anisotropy of Co\(_{20}\)Fe\(_{60}\)B\(_{20}\) was quantified by the coefficients \(K_1 = 5 \times 10^3\) J m\(^{-3}\) [13] and \(K_2 = 50\) J m\(^{-3}\) [4], while the interfacial anisotropy \(-\) by the parameters \(K_0^s = -1.3 \times 10^{-3}\) J m\(^{-2}\) [11] and \(k_s = 31\) fJ V\(^{-1}\) m\(^{-1}\) [14]. The junction’s conductance \(G_p\) at the chosen MgO thickness \(t_b = 1.1\) nm was taken to be \(2 \times 10^{10}\) S m\(^{-2}\) [15], and we used typical asymmetry parameter \(\eta = 0.577\) [11] which yields the tunneling magnetoresistance ratio \(\text{TMR} = (G_p - G_{AP})/G_{AP} = 100\%\).

We studied the magnetic response of FL to the direct current with the predetermined density \(J\) instantly applied to the MTJ, focusing on positive currents that correspond to the tunneling of electrons into PL. In addition to the FL characterized by the intrinsic Gilbert damping parameter \(\alpha_0\), we investigated the case of FL covered by the Au capping layer (figure 1), where the damping becomes higher due to the spin pumping into the normal metal [16] \((\alpha \simeq \alpha_0 + \delta \alpha \approx 0.013,\) see below\). Figure 2 shows the calculated two-dimensional diagram of magnetic responses, where the current density \(J\) and the FL thickness \(t_f\) are used as two variables.

![Figure 2](image)

**Figure 2.** "Current density-thickness diagrams" of magnetic responses of free Co\(_{20}\)Fe\(_{60}\)B\(_{20}\) layers with bare upper surface (a) and Au capping layer (b). The free layer with the in-plane dimensions \(L_1 = 200\) nm and \(L_2 = 80\) nm is subjected to magnetic field \(H_2 = 250\) Oe, at which the thickness-induced SRT occurs at \(t_{SRT} = 1.718\) nm.

At current densities below some critical value \(J^*(t_f)\), the FL magnetization simply deviates from the initial out-of-plane direction \(\mathbf{M}(J = 0)\), leaning towards the pinned magnetization due to the change \(\Delta K_s = k_sJ/(Gl_b)\) in the interfacial anisotropy and the appearance of STT in Eq. (1). Above \(J^*(t_f)\), three different types of dynamical responses become possible, varying with the proximity of \(t_f\) to the critical thickness \(t_{SRT}\), at which the size-driven SRT takes place at the given magnetic field \(\mathbf{H}_{\text{ext}} = \mathbf{H} + \mathbf{H}_{\text{rec}}\). In the vicinity of \(t_{SRT}\), the FL magnetization \(\mathbf{M}\) loses stability against electrically induced precessional motion, which eventually leads to the switching...
of $\mathbf{M}$ into the in-plane direction parallel to $\mathbf{M}_{\text{pin}}$ stabilized by the VCMA [figure 3(a)]. However, such switching (by less than $90^\circ$) occurs within a small region of $J$-$t_f$ diagram only (see figure 2), being replaced by a dynamic SRT at $J > J^* + \Delta J^*$. This novel transition is distinguished from the usual SRT by the appearance of a steady-state magnetization precession around an in-plane axis parallel (type I) or antiparallel (type II) to $\mathbf{M}_{\text{pin}}$. At relatively low current densities, the magnetization first precesses near its initial out-of-plane direction and then assumes large-angle steady-state precession around another direction, which is parallel to $\mathbf{M}_{\text{pin}}$ ($m_2 > 0$) [figure 3(b)]. Hence, this dynamic SRT involves a transition between two different precessional states. In contrast, above some threshold density $J_{th}$, the SRT occurs between the FL initial static state and the dynamic state, where the magnetization precesses around the axis antiparallel to $\mathbf{M}_{\text{pin}}$ ($m_2 < 0$) [figure 3(c)].

Figure 3. Magnetization trajectories in the free Co$_{20}$Fe$_{60}$B$_{20}$ layer with in-plane dimensions $L_1 = 200$ nm and $L_2 = 80$ nm subjected to magnetic field $H_2 = 250$ Oe. The density of applied current and the CoFeB thickness are set equal to $J = 0.35 \times 10^9$ A m$^{-2}$ and $t_f = 1.717$ nm (a), $J = 1.5 \times 10^9$ A m$^{-2}$ and $t_f = 1.71$ nm (b), and $J = 4 \times 10^9$ A m$^{-2}$ and $t_f = 1.71$ nm (c). In all cases the CoFeB layer is covered by the Au layer.

Evidently, the predicted dynamic SRT is caused by the combined action of the STT, which generates magnetization precession, and the VCMA, which alters the energetically favorable magnetization orientation due to a voltage-induced change of $K_s$. Figure 2 shows that the dynamic SRT occurs in a finite range of current densities only, being replaced by the magnetization switching at $J > J^{**}(t_f)$. Interestingly, the magnetization switching at such high current densities results in an antiparallel orientation of $\mathbf{M}$ and $\mathbf{M}_{\text{pin}}$, which is due to the impact of STT. As demonstrated by figure 4, the critical density $J^*$ varies considerably with the FL aspect ratio $L_1/L_2$, whereas $J^{**}$ appears to be only weakly dependent on this ratio. The comparison of panels (a) and (b) in figures 2 and 4 also shows that higher damping parameter $\alpha$ increases both $J^*$ and $J^{**}$.

Since the dynamic SRT gives rise to a large-angle magnetization precession with the frequency in the GHz range, the Co$_{20}$Fe$_{60}$B$_{20}$/MgO/Co$_{20}$Fe$_{60}$B$_{20}$ junction can be used as an electrically driven injector of oscillating spin current into a normal metal or semiconductor. To illustrate this possibility, we evaluated the spin current pumped into the Au overlayer by the 1.746-nm-thick Co$_{20}$Fe$_{60}$B$_{20}$ FL excited by the direct current with the density falling into the precession window $J^* < J < J^{**}$. The spin-current density $\mathbf{J}_{sp}$ [17] near the Co$_{20}$Fe$_{60}$B$_{20}$/Au interface was calculated from the relation $\mathbf{e}_s \cdot \mathbf{J}_{sp} \equiv (\hbar/4\pi) \text{Re}[g_{r\uparrow\downarrow}] \mathbf{m} \times d\mathbf{m}/dt$, where $\mathbf{e}_s$ is the unit vector in the direction of spin flow and $g_{r\uparrow\downarrow}$ is the spin-mixing conductance [18]. Using the results obtained for the current-driven steady-state magnetization precession $\mathbf{m}(t)$ and taking $(e^2/\hbar)\text{Re}[g_{r\uparrow\downarrow}] \approx 4.66 \times 10^{14}$ $\Omega^{-1}$ m$^{-2}$ [18], we determined the spin-current densities $J_{sp}^{\uparrow\downarrow}(t)$ ($k = 1, 2, 3$) in the Au overlayer, which are related to the components $P_k$ of the polarization of spin
Figure 4. "Current density-aspect ratio" diagrams of magnetic responses of free Co$_{20}$Fe$_{60}$B$_{20}$ layers with bare upper surface (a) and Au capping layer (b). The CoFeB layer, not subjected to external magnetic field, has the thickness $t_f = 1.746$ nm, aspect ratio $L_1/L_2$, and width $L_2 = 40$ nm.

current flowing along the $x_3$ axis. Representative time dependences of $J_{3k}^{sp}(t)$, which are shown in figure 5, demonstrate that the density $J_{32}^{sp}$ is distinguished from $J_{31}^{sp}$ and $J_{33}^{sp}$ by the presence of a dc component exceeding the amplitude of spin-current oscillations. The spin pumping into the Au overlayer increases the damping of the magnetization precession in the Co$_{20}$Fe$_{60}$B$_{20}$ FL [16], which can be described by the introduction of the modified Gilbert parameter $\alpha \cong \alpha_0 + \delta \alpha$ calculated to be about 0.013 in our case.

Figure 5. Spin pumping into the Au overlayer generated by the magnetization precession appearing in the free Co$_{20}$Fe$_{60}$B$_{20}$ layer at $J = 4 \times 10^9$ A m$^{-2}$ and $H_2 = 0$. The spin-current densities $J_{3k}^{sp}$ at the interface are calculated for the free layer with the parameters $L_1 = 300$ nm, $L_2 = 40$ nm, and $t_f = 1.746$ nm.
Owing to the inverse spin Hall effect, the pumped spin current also gives rise to a transverse charge current flowing in the normal metal [19]. The density $J_c$ of such current is given by the relation $J_c = \alpha_{\text{SH}}(2e/\hbar)(\mathbf{e}_s \times (\mathbf{e}_s \cdot \mathbf{J}_{\text{sp}}))$, where $\alpha_{\text{SH}}$ is the spin Hall angle. Hence the spin-current density $J_{\text{sp}}$ manifests itself in the charge current flowing along the $x_1$ axis in figure 1, which can be used for experimental detection of spin pumping. For example, the spin pumping from the 1.746-nm-thick FL with dimensions $L_1 = 280$–$400$ nm and $L_2 = 40$ nm at the applied current with density $J = 4.25 \times 10^9$ A m$^{-2}$ generates a transverse direct charge current with a density $J_c \approx 5.3 \times 10^6$ A m$^{-2}$ near the interface.

In summary, we described the impact of the direct current on the Co$_{20}$Fe$_{60}$B$_{20}$/MgO/Co$_{20}$Fe$_{60}$B$_{20}$ tunnel junctions with electric-field-dependent interfacial anisotropy, focusing on junctions involving ultrathin free layers with relatively weak perpendicular magnetic anisotropy and in-plane magnetized pinned layers. By numerically solving the Landau-Lifshitz-Gilbert-Slonczewski equation, we determined possible magnetic responses of free layers having the thickness near the critical value, below which the perpendicular magnetic anisotropy appears due to the increased contribution of the Co$_{20}$Fe$_{60}$B$_{20}$|Au interface to the effective volumetric energy density. The results of numerical calculations were presented in the form of two-dimensional magnetic diagrams, where the current density and the free-layer thickness or aspect ratio are used as variables. Remarkably, a current-density window has been found, within which the dynamic spin reorientation transition takes place, resulting in the appearance of a large-angle steady-state magnetization precession in the free layer. The spin pumping into the Au overlayer caused by such precession has been calculated as well.

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