Controllable Spin-Transfer Torque on an Antiferromagnet in a Dual Spin-Valve

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We consider current-induced spin-transfer torque on an antiferromagnet in a dual spin-valve setup. It is demonstrated that a net magnetization may be induced in the AFM by partially or completely aligning the sublattice magnetizations via a current-induced spin-transfer torque. This effect occurs for current densities ranging below $10^6$ A/cm$^2$. The direction of the induced magnetization in the AFM is shown to be efficiently controlled by means of the magnetic configuration of the spin-valve setup, with the anti-parallel configuration yielding the largest spin-transfer torque. Interestingly, the magnetization switching time-scale $\tau_{\text{switch}}$ itself has a strong, non-monotonic dependence on the spin-valve configuration. These results may point toward new ways to incorporate AFMs in spintronic devices in order to obtain novel types of functionality.

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$S_{0,j}$ is the magnetization amplitude of sublattice $j$, $I$ is the applied current bias, and $V$ is the volume of the system. The effective field $H_{\text{eff},j}$ acting on magnetic sublattice $j$ may be defined as:

$$H_{\text{eff},j} = -\frac{\partial F}{\partial S_j}$$

where $F$ is the free energy per unit volume. Here, $S_j = S_1 S_j$ and we assume $S_1 \simeq S_2 = S_0$. The free energy of the AFM is taken in the form

$$F = \frac{H_E}{4S_0}M^2 + \frac{H_{\text{an}}}{S_0}(L_x)^2 - \frac{H_{\text{an}}^4}{8S_0^4}[(L_x)^4 + (L_y)^4 + (L_z)^4] - H_0 \cdot M,$$

where we have defined the FM and AFM order parameters:

$$M = S_1 + S_2, \quad L = S_1 - S_2.$$

This corresponds to a tetragonal anisotropy with the easy axes ($y$ and $z$) in the AFM plane, and also incorporates the strong exchange coupling $H_E$ between the magnetic sublattices. The above constitutes a system of non-linear coupled equations for the magnetization $S_j$ of sublattice $j$. In order to make contact with a realistic experimental situation, we now discuss the choices for parameter values. We set $2\mu_0 S_0 = 0.1$ T, $\mu_0 = 4\pi \times 10^{-7}$ Tm/A, $V = 120 \times 60 \times 1.5$ nm$^3$, and $\nu = 0.3$ as a moderate estimate. To model a realistic antiferromagnet, the spin exchange coupling and anisotropy fields are taken as $H_E = 400$ T and $H_{\text{an}} = 0.01$ T, $H_{\text{an}}^4 = 0.02$ T$^4$. The Gilbert damping constant is set to $\alpha = 0.001$ ($\alpha_1 = \alpha_2$) and the sublattice magnetizations are assumed to be slightly shifted from their equilibrium position (AP to each other, $s_1 = -s_2$) at $t = 0$ by an angle $\theta / \pi = 0.005$, and set $\varepsilon = 1$. We also introduce the spin-flop transition field

$$H_{sf} = 2\sqrt{H_{\text{an}}^4 H_E}$$

for later use, which is $\simeq 5$ T with the above choice of parameters. The model under consideration is summarized in Fig. 2. For details concerning the solution method of the LLG-equation, see the Appendix.
FIG. 3: (Color online). Time-evolution for $l_z$ (left panel) and $m_z$ (right panel) in an AP spin-valve configuration ($\Omega = \pi$). The arrows point in the direction of increasing current: $I = \{0.02, 0.04, 0.06, 0.08, 0.10\}$ mA.

III. RESULTS

In order to investigate quantitatively the magnetization dynamics, we have solved the full LLG-equation numerically. The time-coordinate has been normalized to $\tau = \gamma M_b l [19]$. We begin by focusing on the results obtained when the spin-valve configuration is AP, i.e. $\Omega = \pi$. The corresponding results are shown in Fig. 3 for a current bias of $I = 1$ mA without any external field. As seen, the AFM order parameter $I$ and FM order parameter $m$ display qualitatively different behavior. In the top panel, $I$ exhibits an oscillating decay until it vanishes completely. Remarkably, it is seen from the middle panel that a net magnetization evolves with increasing $\tau$ until it fully saturates in the $z$-direction. The insets show a parametric plot of the time-evolution of the AFM and FM order parameters, the circle denoting its value at $t = 0$. These results indicate that it should be possible to magnetize an AFM exclusively by means of a current-bias in a spin-valve setup. In the lower panel of Fig. 3, we consider how the switching time $t_{\text{switch}}$ depends on the magnitude of the applied current, the switching time defined from $|m(t_{\text{switch}})| \geq 1.95$ (note that the maximum value of both $|m|$ and $|I|$ is 2).

We proceed to investigate how large the current-bias has to be in order for the spin-transfer torque to magnetize the AFM. To answer this, we provide in Fig. 3 both $l_z$ and $m_z$ as a function of $\tau$ for several values of the current strength $I$. As seen, the induced magnetization decreases as the current diminishes. However, even at $I = 0.02$ mA one may observe a partial alignment of the sublattice magnetizations manifested as a finite value of $m_z$. As discussed in Sec. [IV], this corresponds to current densities ranging below $10^6$ A/cm². The AFM order parameter displays an oscillating decay in all cases. For very small currents $I \leq 0.01$ mA, we found no appreciable induced magnetism when solving the above equations of motion.

Instead, the AFM order parameter $I$ undergoes a precessional motion and spin-flop transition into the $xy$-plane, similarly to Ref. [20].

It is also of interest to see what happens when the spin-valve configuration is noncollinear, i.e. $\Omega \neq \{0, \pi\}$. In Fig. 4, we solve for the time-evolution of the AFM and FM order parameters for an applied current of $I = 1$ mA with a spin-valve configuration set at $\Omega = 0.5\pi$. As seen, $I$ decays to zero whereas $m$ saturates at a finite value, albeit not fully aligned with either of the easy axes of the system. This shows that it is possible to control the direction of the induced magnetization in the AFM by tuning the spin-valve configuration $\Omega$.

Related to this, it is natural to ask: what influence, if any, does the spin-valve configuration have on the switching time itself? To investigate this, we have plotted the switching time $t_{\text{switch}}$ as a function of $\Omega$ in Fig. 5 for a regime of configurations where switching occurs, comparing two values of the current bias in our numerical calculations. Numerically, $t_{\text{switch}}$ was defined as the time where the magnetization had attained a value of 97.5% of its saturated value. As seen, the switching time is strongly dependent on the configuration $\Omega$. In fact, it behaves in a non-monotonic fashion with a peak value as its most striking feature. Fig. 5 suggests that there exists a spin-valve configuration for a given current bias which strongly delays the magnetization switching, whereas configurations close to AP ($\Omega = \pi$) offer the most rapid switching. The peak position shifts towards the P configuration ($\Omega = 0$) with increasing current which also lowers the overall switching time, as is natural since the spin-transfer torque becomes stronger. The variation in switching time as obtained when varying $\Omega$ is seen to span over more than an order of magnitude from Fig. 5.

IV. DISCUSSION

In order to understand the induced magnetic moment in the AFM qualitatively, one should note that the current-induced spin-transfer torque described by Eq. (2) acts in the same direction even after applying the transformation $s_j \rightarrow -s_j$. Hence, both magnetic sublattices in the AFM will experience a torque in the same direction upon application of a current-
bias and thus inducing a net magnetic moment. The stability range of the induced moment, i.e., whether it persists over time, depends on the other system parameters such as anisotropy field and exchange bias, as we have discussed. To observe the proposed effects, it is necessary to experimentally adjust the spin-valve configuration. Presumably, this will be most efficiently done by selecting ferromagnets with different properties for the left and right layer. An exchange interaction with the fixed (left) magnetic layer should determine the initial orientation of the AFM order parameter \( \mathbf{I} \), taken to be along the \( z \)-axis in this case, although this interaction should be sufficiently small that it may be disregarded under the influence of a current-bias.

A key parameter in terms of the current-induced spin-transfer torque is the required current density to obtain the induced magnetization \( \mathbf{M} \). As seen from Eqs. (1) and (2), the torque is proportional to both the current density and the cross-sectional area of the AFM while being inversely proportional to the total volume of the AFM. Assuming a cross-sectional area of \( 120 \times 60 \) nm\(^2\), it follows that the predicted effects in this paper occur for current densities even below \( 10^6 \) A/cm\(^2\) (corresponding to a total current \( \sim 0.1 \) mA). To further characterize the robustness of the reported effects, such as the non-monotonic switching-time\(^2\), it could be useful to apply micromagnetic theory to the proposed spin-valve structure. Moreover, the characterization of other properties such as how the GMR is influenced by the antiferromagnetic layer could provide further insight in how the magnetic configuration interacts with the presence of AFM in the middle free layer.

### V. SUMMARY

In summary, we have calculated the magnetization dynamics of an antiferromagnet in a dual spin-valve setup, taking into account anisotropy effects and current-induced torques. We have shown that it is possible to induce a net magnetization in the AFM by partially or completely aligning the sublattice magnetizations via a current-induced spin-transfer torque. Moreover, the direction of the induced magnetization in the AFM can be efficiently controlled by means of the magnetic configuration of the spin-valve setup. Remarkably, the magnetization switching time-scale itself is found to be controllable via the spin-valve setup: it displays a highly non-monotonic dependence on the magnetization configuration. The obtained results appear in an experimentally feasible parameter regime, and may thus point toward new ways to incorporate AFMs in spintronic devices in order to obtain novel types of functionality.

### Appendix

We here provide some additional details concerning the method of solution for the LLG-equation. By direct algebraic manipulation, one may write Eq. (1) as:

\[
\hat{\mathbf{A}} \mathbf{x} = \mathbf{B}
\]

where \( \mathbf{x} = [s_{x1}, s_{y1}, s_{x2}, s_{y2}]^T \), where \( T \) denotes the matrix transpose. We have defined the matrices:

\[
\hat{\mathbf{A}} = \begin{pmatrix} \mathcal{A}_1 & 0 \\ 0 & \mathcal{A}_2 \end{pmatrix}, \quad \mathcal{A}_j = \begin{pmatrix} -1 & -\alpha s_{jy} & \alpha s_{jy} \\ \alpha s_{jy} & -1 & -\alpha s_{jx} \\ -\alpha s_{jx} & \alpha s_{jx} \end{pmatrix}, \quad j = 1, 2.
\]

in addition to \( \mathbf{B} = [b_1, b_2]^T \) with:

\[
b_j = \begin{pmatrix} \gamma(s_{jy}H_{jy} - s_{jy}H_{jy}) - T_{jy} \\ \gamma(s_{jy}H_{jy} - s_{jy}H_{jy}) - T_{jy} \\ \gamma(s_{jy}H_{jy} - s_{jy}H_{jy}) - T_{jy} \end{pmatrix} = \begin{pmatrix} b_{jy} \\ b_{jy} \\ b_{jy} \end{pmatrix}, \quad j = 1, 2.
\]

The above system of equations may then be solved to yield uncoupled equations in the time-derivative of the magnetization sublattices \( s_j \), which read:

\[
\dot{s}_{jy} = -\frac{1}{1 + \alpha^2} \left[ \alpha^2(s_{jy}^2b_{jy} + s_{jy}^2b_{jy} + s_{jy}^2b_{jy}b_{jy}) + \alpha(s_{jy}^2b_{jy} - s_{jy}^2b_{jy}) + b_{jy} \right]
\]

\[
\dot{s}_{jx} = -\frac{1}{1 + \alpha^2} \left[ \alpha^2(s_{jx}^2b_{jx} + s_{jx}^2b_{jx} + s_{jx}^2b_{jx}) + \alpha(s_{jx}^2b_{jx} - s_{jx}^2b_{jx}) + b_{jx} \right]
\]

\[
\dot{s}_{jy} = -\frac{1}{1 + \alpha^2} \left[ \alpha^2(s_{jy}^2b_{jy} + s_{jy}^2b_{jy} + s_{jy}^2b_{jy}) + \alpha(s_{jy}^2b_{jy} - s_{jy}^2b_{jy}) + b_{jy} \right]
\]

\[
\dot{s}_{jx} = -\frac{1}{1 + \alpha^2} \left[ \alpha^2(s_{jx}^2b_{jx} + s_{jx}^2b_{jx} + s_{jx}^2b_{jx}) + \alpha(s_{jx}^2b_{jx} - s_{jx}^2b_{jx}) + b_{jx} \right]
\]
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