Vortex Dynamics in Multilayered Nanopillar Element – Spin-Transfer Torque Magnetic Random Access Memory (STT-MRAM)

B. C. Choi, J. Kolthammer, J. Rudge, A. Santoni, H. Xu, and C. Burrowes

Department of Physics and Astronomy, University of Victoria, BC, V8W 3P6, Canada

There has been substantial progress in the understanding of the nonequilibrium magnetization process in micro- and nanosized elements. In particular, the high-speed magnetization dynamics in the vortex state has drawn increasing attention due to fundamental interest and to its possible applications in high-density magnetic storage devices. Recently, the switching of the vortex magnetization state by applying short bursts of an alternating magnetic field[1] or a single magnetic pulse[2,3] has been extensively investigated. For practical applications, however, it is desirable to find a more practical method, i.e., current-driven switching of the magnetization state of the vortex by utilizing spin-torque effect[4,5].

We discuss detailed micromagnetic studies of the nonequilibrium magnetization process of the vortex magnetization in multilayered nanopillar structure. We demonstrate that the vortex chirality can be controllably switched by injecting a current pulse with appropriate amplitude, polarity, and duration. Fig. 1(a) is a schematic of the multilayered pillar structure. The pillar has a diameter of 100 nm, and the fixed magnetic layer (20 nm Co) is separated from the free magnetic layer (6 nm Py) by a 4 nm thick Cu spacer layer. The initial vortex states of the Py (b) and Co (c) layers are identified as CCW-positive ($V_{\uparrow}^{CCW}$) based on their chirality, and positive polarities of the core magnetizations.

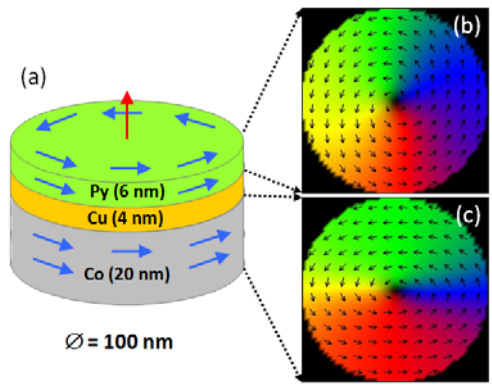

Fig. 1 Schematic of the nanopillar structure. Details are found in the text.

To study the dynamic response of the vortex magnetization to the spin-transfer torque, the equilibrium configurations of $\mathbf{M}_{Py}$ and $\mathbf{M}_{Co}$ are excited by injecting a short current pulse. The current direction is denoted positive when it flows from Py to Co. Fig. 2 shows a series of the nonequilibrium states of $\mathbf{M}_{Py}$ captured at selected times after a current pulse of –30 mA in amplitude with the duration of 200 ps is applied. The rise and fall time of the current pulses is assumed to be 2 ps. Following the temporal evolution of $\mathbf{M}_{Py}$ in Fig. 2, one finds that individual $\mathbf{M}_{Py}$ undergoes the CW rotation, while the whole vortex configuration appears to circulate CCW around the disk center. The image (b), captured at 84 ps after the current pulse is applied, reveals that $\mathbf{M}_{Py}$ rotates by ~90°, and with increasing time $\mathbf{M}_{Py}$ further rotates by ~180° (c), i.e., the chirality of $\mathbf{M}_{Py}$ switches from CCW (a) to CW (c) after about a half-cycle of rotation. $\mathbf{M}_{Py}$ of the switched vortex state in (c), however, is still in a nonequilibrium state, and the dynamics of the energy dissipation after the initial chirality switching involves a series of complex magnetization processes. The magnetization configuration in (d), for instance, reveals a high degree of complexity both due to the nonunifrom distribution of $\mathbf{M}_{Py}$ and the creation of an additional vortex ($V^{\uparrow}$)-antivortex (V^{A}) pair. The pair vanishes with increasing time without undergoing an annihilation process. We note that the vortex core dynamics in Fig. 2 is different from the previously reported results[2,3] in which the polarity of vortex core was reversed via the explosion-like annihilation of vortex-antivortex pair after the vortex magnetization was excited by an in-plane magnetic field pulse. A full relaxation of $\mathbf{M}_{Py}$ is reached after about 2 ns after the current pulse excitation (e). By contrast, the magnetization distribution of $\mathbf{M}_{Co}$ is only slightly perturbed from the initial state through the entire process of the chirality switching of $\mathbf{M}_{Py}$, and no switching of vortex chirality of $\mathbf{M}_{Co}$ occurs (f). Therefore, the curling in-

plane magnetizations of $\mathbf{M}_{Py}$ and $\mathbf{M}_{Co}$ is aligned nearly antiparallel to each other after the reversal of the vortex chirality of $\mathbf{M}_{Py}$ is completed.

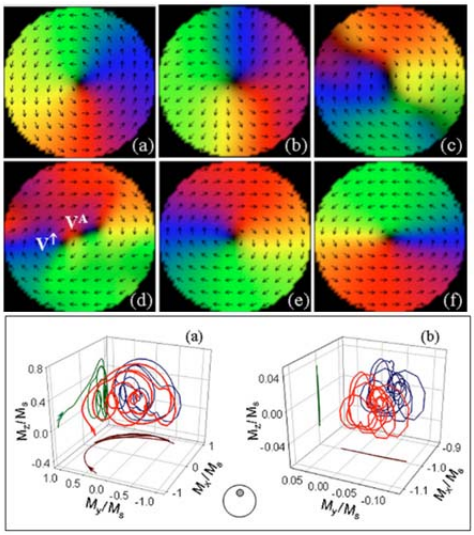

FIG. 2 (*top panel*) Nonequilibrium magnetization distributions of $\mathbf{M}_{Py}$ at selected time points after the onset of a current pulse of −30 mA with 200 ps duration: (a) 0 ps, (b) 84 ps, (c) 114 ps, (d) 178 ps, and (e) 2 ns after the current pulse. (f) $\mathbf{M}_{Co}$ distribution captured at 2 ns after the current pulse. Each arrow indicates the averaged local magnetization from four unit cells. (*bottom panel*) Three-dimensional trajectory of the magnetization averaged over the area of 10 nm in diameter, as indicated by the shaded area in the inset. (a) The trajectory reveals an initial rapid rotation of $\mathbf{M}_{Py}$ from $-M_x$ to $+M_x$, and the spin torque induced by the current pulse tilts the magnetization vector out of the *x-y* plane. (b) Dynamic response of $\mathbf{M}_{Co}$ components. Note that the scale of the axis is an order of magnitude smaller than that in (a). This indicates that $\mathbf{M}_{Co}$ resists the spin-transfer torque by the spin-polarized electrons partly reflected from the Cu/Py interface.

In order to obtain a more detailed understanding of the magnetization dynamics induced by spin-torque transfer to the vortex magnetization, the actual direction of $\mathbf{M}_{Py}$ and $\mathbf{M}_{Co}$ during the chirality switching is reconstructed. The bottom panel of Fig. 2 shows the three-dimensional magnetization trajectory and corresponding projections of the M_x, M_y, and M_z components of $\mathbf{M}_{Py}$ and $\mathbf{M}_{Co}$. For $\mathbf{M}_{Py}$, the trajectory reveals an initial rapid reversal of M_x component immediately after the current pulse. The spin-transfer torque also tilts $\mathbf{M}_{Py}$ out of the *x-y* plane. After the main reversal process, i.e., M_x/M_s for Py from −1 to +1, the trajectories of M_y^{Py} and M_z^{Py} follow rotational paths. Therefore, it is concluded that the magnetic response to the spin torque leads to an irreversible switching of M_x^{Py}, accompanied by the precession of $\mathbf{M}_{Py}$ around the *x* direction. The trajectory of $\mathbf{M}_{Py}$ following a rotational path is reminiscent of the magnetization precession, observed in the magnetization reversal driven by short magnetic field pulses[6]. However, the dynamics of the precession in response to the spin-transfer torque is not of a uniform excitation mode, and develops a more complex pathway. The Fourier transform of the magnetization components of M_x/M_s for Py yields a relatively broad peak centered around 16 GHz along with a large low frequency response at 4 GHz. The Fourier transform shows a quite different frequency spectrum, if the spin-torque effect is excluded in the modeling. In this case, no significant peaks are found, implying a high degree of incoherence in the precession due to spin-wave excitation triggered by vortex-antivortex pair annihilation and subsequent complex behaviour of magnetization dynamics.

In summary, dynamics of vortex chirality switching in a magnetic multilayer has been discussed. We demonstrate that the spin-transfer torque provides a new means to controllably switch the vortex chirality. From an application point of view, the results suggest opportunities to implement the chirality switching mechanism to memory device applications, in which vortex states with controllable chirality switching in the free layer of a magnetic nanopillar may be used as memory bits.

References

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