Precessional switching of submicrometer spin valves

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Small spin valves are switched using a subnanosecond field pulse applied along the magnetization hard axis. The measured probability for switching due to pulsed hard-axis fields increases as the duration is decreased from 325 to 230 ps. This indicates a large-angle precessional motion in response to the transverse applied field. The behavior is modeled with a single-domain, Landau–Lifshitz simulation. Switching in this manner requires only single-polarity transverse pulses that toggle the state of magnetic devices. This process consumes less energy than traditional quasi-static switching using long-duration field pulses along both directions. [DOI: 10.1063/1.1470704]

The nature of magnetization reversal in small, patterned magnetic devices is of particular importance for the successful operation of magnetic random-access memory (MRAM).[1] Current MRAM prototypes rely on magnetic field pulses to switch between two stable states of the magnetic device. The field pulses have durations and rise times[2] $\geqslant 2$ ns. In this regime, the reversal is quasi-static with the device following a trajectory of minimum energy states. An alternative method for magnetization reversal is a direct dynamical process requiring a larger field amplitude but much smaller field duration. The Landau–Lifshitz (LL) equation, $d\mathbf{M}/dt = -\mu_0\gamma\mathbf{M}\times\mathbf{H} - \alpha(\mu_0\gamma/|\mathbf{M}|)\mathbf{M}\times(\mathbf{M}\times\mathbf{H})$ provides a simple model to describe the response of a single-domain magnetization, $\mathbf{M}$, to the net magnetic field, $\mathbf{H}$. Here, $\gamma = 2\pi\times 28$ GHz/T is the gyromagnetic ratio and α is the damping parameter ($\alpha \sim 0.03$ for devices considered here). The first term describes a precessional motion of $\mathbf{M}$ about $\mathbf{H}$. The second term applies damping, and forces $\mathbf{M}$ to relax into the lowest energy configuration with $\mathbf{M}\|\mathbf{H}$. For quasi-static switching, the damping term is sufficient to describe the motion of the magnetization. For high speed switching, as described in this letter, the precessional term accounts for much of the magnetization motion, which occurs on a time scale too short for significant damping to occur.

For the magnetic materials used in current devices, ~ 2 ns are required to damp out precession for small-angle motions of the magnetization.[3–5] Simulations have shown[6] that the response of magnetic particles to field pulses with duration less than the damping time results in switching phase diagrams much more complex than the standard Stoner–Wohlfarth switching astroid.[7] This is because the trajectory of precessional motion is very sensitive to the field amplitude and duration, and the magnetization does not significantly relax during the application of the field. The nature of this precessional motion has been previously observed in bulk cobalt films driven by picosecond duration field pulses.[8] In this letter, we demonstrate the reversal of a spin valve using 230–300 ps hard-axis field pulses. This switching process shows several characteristics of precessional behavior, including a transition from switching to not switching as pulse duration is *increased* and the ability to toggle the state of the device with the same polarity pulse.

Spin valves were fabricated within high-bandwidth test structures of the same design as those previously used for measuring spin-valve dynamic effects.[4,5,9] The device terminates a 2 μm wide, 50 Ω microstrip line (sense line), that transmits the voltage pulse due to magnetization rotation of the free layer. A 4 μm wide, 50 Ω microstrip line (write line) above the device provides spatially uniform, subnanosecond field pulses to the device. A commercial generator provides 50 ps rise time, 10 V pulses with variable duration from 100 ps to 10 ns. Bandwidth limitations of the waveguide structures increase the actual field pulse rise time to 100 ps and broaden the minimum pulse width to 230 ps. The pulsed magnetic field amplitude H_p was estimated by assuming a uniform sheet current from the write line, $H_p = V/(2Zw)$, where $Z = 50\ \Omega$ is the impedance of the microstrip line, $w = 4\ \mu$m is its width, and V is the voltage amplitude of the pulse at the device.

Optically patterned, rectangular-shaped spin valves were studied. The devices achieve a high pinning field (>80 kA/m) using a synthetic antiferromagnet pinning structure.[10] The spin-valve free layer composition is $Ni_{0.8}Fe_{0.2}$ (2.5 nm)/Co(1 nm). The devices are pinned along the easy axis. The high resistance state is the antiparallel alignment of the free and pinned-layer magnetizations, and the low resistance state occurs when the magnetizations are parallel. The devices are stable in both configurations at zero-applied field. However, the magnetoresistance (MR) loops are shifted in field by H_{co} resulting in a lower switching field for accessing the parallel state as compared to the antiparallel state. This is characteristic of magnetostatic "orange peel" coupling.[11]

Device switching probability was determined by measuring 100 events in which the device was subjected to identical field pulses, the remanent state was read, and the device was reset by a 12 kA/m (150 Oe) external field directed along the initial magnetization direction.[12] The pulse amplitude was fixed at 17.2 kA/m (216 Oe),[13] and the pulse duration was swept from 230 to 325 ps. An additional longitudinal bias field $H_L = -2$ kA/m was added to negate the coupling field. The field shift due to the magnetostatic coupling, $H_{co} = 2$ kA/m, was determined from a quasi-static MR loop. The

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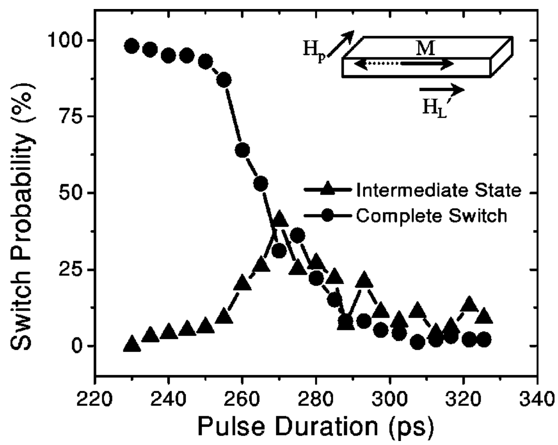

FIG. 1. Probability of switching for a 0.45 μm$\times$1.15 μm device vs pulse duration. Dots indicate probability of complete switching, and triangles indicate probability of remanent intermediate state. Inset: Field pulses H_p are along the hard axis. H_L' is the effective bias field in the easy-axis direction. M gives the initial free layer magnetization direction.

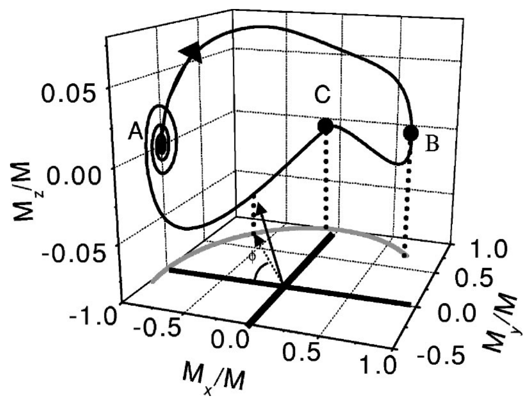

FIG. 2. Magnetization trajectory of a simulated device responding to a 400 ps, trapezoid-shaped hard-axis pulse with 100 ps rise time. The z axis (out-of-plane) scale is greatly expanded compared to the easy x axis and hard y axis. Trajectory follows the direction given by the arrow. Point A is the initial magnetization direction. Point B is the maximum excursion of the magnetization. Point C is where H_p turns off. The gray curve gives the in-plane projection of the trajectory.

effective field along the easy axis is given by $H_L'=H_{co}+H_L$, and here $H_L'=0$.

Figure 1 shows the switching probability of a 0.45 μm $\times$1.15 μm device as a function of the hard-axis field pulse duration (orientations of the fields are shown in the inset). The data show that the probability of switching decreases to zero as the pulse duration was increased. This is opposite to the behavior observed in response to easy-axis pulses[9] and can be explained by the device magnetization dynamics. The hard-axis field applies a large torque on the magnetization causing large-angle precession. The strong out-of-plane demagnetizing field causes the magnetization to rotate, mostly in plane, between opposite stable states of the spin valve while the field is on and before damping has become significant. The process requires a large enough field and short enough rise time for the magnetization to overshoot the hard axis during the application of the pulse. During the first oscillation cycle, a short duration field pulse, which turns off while the magnetization is near the opposite end of the spin valve, will cause the device to switch. A slightly longer field pulse will allow the magnetization to rotate back towards the initial state, resulting in a no-switch event after the field turns off. This is shown in Fig. 2, which contains a calculated trajectory of **M** responding to a 400 ps hard-axis field pulse. The trajectory was calculated using the LL equation with $\alpha=0.03$. The field turns off at point C, at which point **M** is close enough to the initial state that it relaxes back to that orientation. If the field terminated near point B (field duration$=$250 ps), then **M** would relax to the switched state.

Simulations using the LL equation were performed to determine how the switching transition compares with the experimental data in the case of transverse applied field pulses. The simulations can be used to observe how the dynamics are effected by pulse amplitude, pulse duration, longitudinal bias field, and damping. The demagnetizing factors were adjusted to give an anisotropy field H_k of 22 kA/m (276 Oe), which was the measured H_k for the device. The saturation magnetization used was $M=1049$ kA/m, which was the thickness-weighted average of the NiFe and Co magnetization in the free layer. Figure 3(a) shows the simulation results for $\alpha=0.03$, in the form of a switching phase diagram, where the x axis gives H_L' with positive field pointing along the initial device magnetization direction. The y axis gives the duration of a trapezoidal, 20.3 kA/m hard-axis field pulse. The pulse shape approximately matched the experimental field pulses with a rise time of 100 ps and a fall time of 300 ps. For $H_L'=0$, the simulated device switched only for pulses with duration less than 290 ps. This is close to the measured switching transition at 270 ps which is shown in Fig. 1. The simulation implies that hard-axis field pulses with duration less than 290 ps perform a toggle operation on the magnetic state of the device. The device experimentally exhibits toggling behavior in response to 230 ps duration pulses.

Figure 3(b) shows the limiting case for long pulse duration with a larger rise time of 400 ps. The simulation predicts no switching at $H_L'=0$ because **M** relaxes to its equilibrium orientation angle $\phi_0=\sin^{-1}(H_p/H_k)$ during application of H_p. Here, ϕ_0 is the in-plane angle measured relative to the

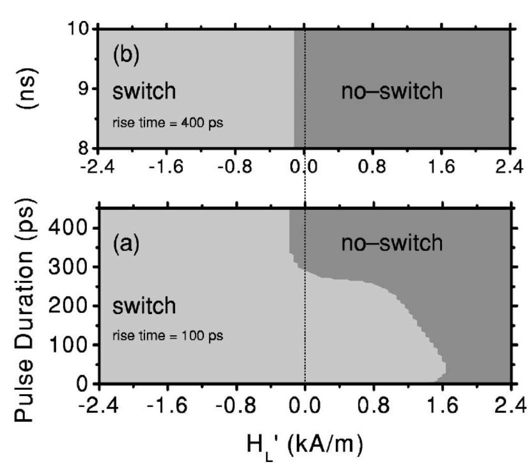

FIG. 3. Switching phase diagram from single-domain simulation. H_L' is along the x axis and pulse duration is along the y axis. Light areas represent a switch; dark areas represent no switch. Simulated device has $H_k=22$ kA/m and damping parameter $\alpha=0.03$. The pulse amplitude is $H_p=20.3$ kA/m. (a) Dynamic response to 100 ps rise time pulses. Here, the switching transition at zero longitudinal bias occurs at a pulse duration of 290 ps. (b) Adiabatic response to 400 ps rise-time pulses.

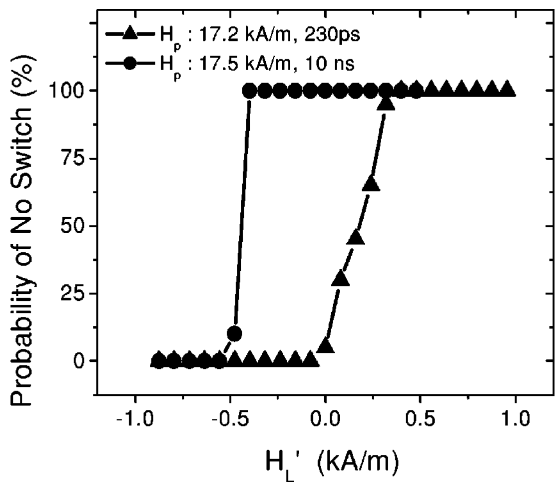

FIG. 4. Probability of *not switching* for a 0.45 μm$\times$1.15 μm device as a function of effective longitudinal field. Positive H_L' is in the direction of the initial magnetization. Dots indicate the response to 10 ns pulses along the hard axis, and triangles indicate the response to 230 ps pulses along the hard axis.

initial direction of **M**; $\phi_0 = 52.7°$ for $H_p = 17.5$ kA/m. Since $\phi_0 < 90°$, **M** returns to its original orientation when H_p turns off. In fact, the device exhibits this behavior. Figure 4 shows the measured probability of *not switching* in response to a transverse field pulse as a function of H_L'. For 10 ns duration, 400 ps rise time, 17.5 kA/m pulses, the device did not switch until H_L' was directed opposite the initial direction; specifically, $H_L' \leqslant -0.4$ kA/m (-5 Oe). In contrast, switching due to pulses of 230 ps duration, 100 ps rise time, and 17.2 kA/m amplitude began to occur at $H_L' = 0.3$ kA/m (3.8 Oe).

The single-domain simulation qualitatively describes the data, but the quantitative agreement is not good, indicating the importance of micromagnetic (nonuniform magnetization) effects. Values for H_p used in the simulation (20.3 kA/m) to obtain qualitative agreement with the data are larger than the experimental values (17.2 to 18.4 kA/m). A lower damping parameter ($\alpha = 0.01$) in the simulation produced additional switch to no-switch transitions not seen in the experimental data. A larger damping parameter ($\alpha = 0.04$) pushed the switch to no-switch transition to a much larger pulse duration. Thus, $\alpha = 0.03$, which was measured in similar devices undergoing small angle motions,[4] seems an appropriate value for the damping parameter in these simulations where the magnetization moves through a large angle.

Further complications in the comparison of the data to the single-domain simulations exist. One is the observation of switching probabilities between 1 and 0. The single-domain simulation predicts only a deterministic response in which the device switches with probability of exactly 1 or 0. In addition, the appearance of remanent intermediate states in the data is not accounted for by the simulation (see Fig. 1). These states have resistances in the range of 50%–60% of the full switch value, and indicates disorder, which allows significant, long-lived micromagnetic structure in the device. The intermediate states appear during the transition region and overlap both the switching and no-switching region predicted in the single-domain model. It is likely that the intermediate states result from a break up of the magnetization as it relaxes after the drive field has turned off. The probability of incurring these states would be highest around the switching transition where relaxation would require the greatest motion of the magnetization. This is in agreement with the data of Fig. 1. A more realistic model addressing these questions would require a micromagnetic simulation including disorder and thermally activated processes.

Reversal in the dynamic limit requires field pulses of very short duration. It also requires field amplitudes larger than the quasi-static switching field. In this case, the dynamic switching field amplitude is a factor of five larger than the quasi-static switching field. Current MRAM prototypes use write field duration of $\sim$10 ns.[1] This pulse duration would require a field amplitude that is roughly a factor of four less than the dynamic switching field demonstrated here.[9] The energy, ε, required during a write process is given by $\varepsilon \propto H^2 \Delta t$, where H is the field amplitude and Δt is the pulse duration. For the device shown, the dynamic reversal with a 250 ps duration pulse uses less energy per write event by a factor of 2.5 compared to the current MRAM programming scheme.

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[13] Due to bandwidth limitations of the write line, there is a slight increase of pulse amplitude with pulse duration of $\sim$1.19 kA/m per 100 ps. This alters the details of the response, but the interpretation that precession explains the data in Fig. 1 is still valid.