Current-induced switching of magnetization has generated much excitement due to its potential for magnetic random access memory. In spite of the apparent success of the spin-torque model in describing many of the experiments, the basic physical processes involved in the switching are not yet fully understood. Most experimental studies of current-driven magnetization switching in magnetic nanopillars have been made on Co/Cu/Co trilayers at room temperature (295 K) \(2\;\text{to}\;10\). For magnetically uncoupled samples, switching at low current \(I\) and magnetic field \(H\) is hysteretic, but becomes reversible at large enough \(I\) in one direction. This reversibility is associated with telegraph noise switching. In this paper we examine several subleties of switching in Co/Cu/Co that have not been previously described. First, the \(I\) vs. \(H\) switching (magnetization stability) diagrams are slightly different when measured by varying \(H\) while holding \(I\) fixed and vice versa. Second, we show how the reversible switching peak can be calculated from the measurements of telegraph noise dwell times vs. \(I\). Third, we show data for an unusual sample, where a positive reversible switching peak is replaced by a negative one.}

Our samples were fabricated with a multistep process described elsewhere \(10\). The samples had structure Co(20)/Cu(10)/Co(2.5), where thicknesses are in nm. To minimize dipolar coupling between the Co layers, only the Cu(10)/Co(2.5) layers were patterned into a nanopillar with approximate dimensions \(140\times 70\;\text{nm}\). We measured differential resistance, \(dV/dI\), at 295 K with four-probes and lock-in detection, adding an ac current of amplitude 20 \(\mu\text{A}\) at 8 kHz to the dc current \(I\). Positive current flows from the extended to the patterned Co layer. \(H\) is in the film plane along the easy axis of the nanopillar.

Figs. \(\text{I(a,b)}\) show field- and current-switching data, consistent with prior studies \(2\;\text{to}\;10\). Starting, for example, at \(I = 0\) and large negative \(H\), the magnetizations of the thick and thin Co layers are parallel (P). As \(H\) is increased from a large negative value, the magnetization of Co(20) switches first at small positive \(H\) into a high resistance antiparallel (AP) state, and the patterned Co(2.5) switches at larger switching field, \(H_s(I = 0)\), determined by its shape anisotropy. For \(I = -1\;\text{mA}\), Fig. \(\text{I(a)}\) shows reduced \(H_s(I)\), and the hysteretic switching disappears at \(I < -1\;\text{mA}\). \(I > 0\) increases the range of \(H\) for the AP configuration. At \(I > 4\;\text{mA}\), the hysteretic switching steps in \(dV/dI\) turn into reversible peaks \((I = 5\;\text{mA} \text{ shown})\). Fig. \(\text{I(b)}\) shows that hysteretic asym-
metric current-driven switching between the AP state at \( I > 0 \) and the P state at \( I < 0 \) at \( H = 0 \), changes to reversible peaks both at large \( H > 0 \) and \( H < 0 \). These peaks are the same as those in Fig. 1(a) at large \( I > 0 \). The P state resistance grows above a threshold \( I_t \), marked on the \( H = 0.6, 1.4 \) kOe curves. A similar, more pronounced threshold in Py/Cu/Py nanopillars has been associated with the onset of large amplitude magnetic excitations [11]. At small \( H \), the switching from P to AP state occurs at \( I_s \approx I_t \). The small variation of \( I_t \) between 0.6 kOe and 1.4 kOe in Fig. 1(b) is determined by the balance between the current-driven excitation and weakly \( H \)-dependent magnetic damping rate.

Figs. 1(c,d) show the Co(2.5) nanopillar magnetization stability diagrams extracted from \( H \) and \( I \) scans such as those in Figs. 1(a,b), respectively. (We show only the switching of the thin Co layer in Fig. 1(c), to avoid clutter and facilitate comparison with Fig. 1(d).) Both scan directions give similar stability regions, with a minor difference in the line separating the bistable and P-stable regions. At small \( I > 0 \), the stability line in Fig. 1(c) is almost vertical, giving a sharp knee at \( I = 0 \), whereas in Fig. 1(d) it curves smoothly at \( I \approx 0 \). Vertical lines are poorly reproduced by \( I \)-scans, so Fig. 1(c) better captures the singular behavior at \( I \approx 0 \). This knee has been attributed to the effect of spontaneous current-driven magnon emission, generally small compared to stimulated emission [12].

The reversible switching peaks in \( dV/dI \) that at large \( I, H \) replace the hysteretic steps, are due to random telegraph noise switching between the P and AP states [11]. Fig. 2(a) shows the variations of average dwell times \( \tau_P(\tau_{AP}) \) in the P(AP) state with \( I \). \( \tau_P \) decreases as \( I \) increases, but \( \tau_{AP} \) increases. For a fixed \( H \), \( \tau_{AP} << \tau_P \) at small \( I \), so \( dV/dI \) is close to the resistance of the P state, \( R_P \), and \( \tau_{AP} \gg \tau_P \) at large \( I \), giving \( dV/dI \approx R_{AP} \), the resistance in the AP state. We now show how the variations in Fig. 2(a) give a peak in the differential resistance at \( \tau_P \approx \tau_{AP} \). For a given \( H \), the average voltage across the sample is

\[
V(I) = I \left[ \frac{R_{AP} \tau_{AP} + R_P \tau_P}{\tau_P + \tau_{AP}} \right],
\]

where \( \tau_P(I) \approx \tau_0 \exp\left[-\alpha(I - I_0)\right] \), \( \tau_{AP}(I) \approx \tau_0 \exp[\beta(I - I_0)] \), as follows from Fig. 2(a). \( I_0, \tau_0 \) are defined by \( \tau_{AP}(I_0) = \tau_P(I_0) = \tau_0 \). Differentiating Eq. with respect to \( I \), we find

\[
d\tau = \frac{\tau_{AP} R_{AP} + \tau_P R_P}{\tau_P + \tau_{AP}} + \frac{\tau_{AP} \tau_P}{(\tau_P + \tau_{AP})^2}.
\]

The first term on the right is just the resistance \( V/I \), giving a step for the reversible transition from the P to the AP state. The second term has a maximum value \( \tau_0 (\alpha + \beta)(R_{AP} - R_P)/4 \) at \( \tau_P = \tau_{AP} \). This term gives rise to a peak in \( dV/dI \) at \( I = I_0 \), which can be much higher than \( R_{AP} \). The solid line in Fig. 2(b) is calculated from the data in Fig. 2(a), and Eq. 2 for \( I_0 = 4.8 \) mA, and \( \alpha + \beta = 19.2 \) mA\(^{-1} \) extracted from Fig. 2(a). The calculation agrees well with the data shown as circles.

From the above analysis, we conclude that the reversible switching peak positions characterize the points \((H, I)\) where \( \tau_P = \tau_{AP} \), thus giving an indirect measure for telegraph noise variation with \( I \). 

We have shown [11] that the telegraph noise period decreases approximately exponentially when \( I \) is increased and \( H \) is adjusted to remain along the reversible switching line. The presence of telegraph noise near the reversible switching line means that both AP and P states are unstable in that region. Thus, the stability diagrams, Figs. 1(c,d), should be modified to include this unstable region. This instability is indirectly manifested in the rise of \( R_P \) at \( I > I_t \). However, the measurements of \( dV/dI \) at \( I \) above the reversible switching peak give values very close to \( R_{AP} \). Fig. 2 and our analysis show that, because \( \tau_P \) is exponentially smaller than \( \tau_{AP} \), the resistance can become close to \( R_{AP} \), even though the AP state is unstable.

In most samples, both \( I \) and \( |H| \) increase along the reversible switching line close to the transition from hysteretic to reversible switching. The behavior at larger \( I \) varies: in some samples, the reversible switching peak disappears, or splits into several peaks. These peaks are usually asymmetric in \( H \), showing the importance of inhomogeneous and tilted magnetization states, affected both by sample imperfections and the Oersted field of the current. Fig. 3 shows data for a sample nominally identical to that of Fig. 1. The hysteretic MR at \( I = 0 \), and current-driven switching at \( H = 0 \) (Figs. 3(a,b)), are similar to those in Figs. 1(a,b). The \( I = 8 \) mA MR curve in Fig. 3(a) is asymmetric, showing a positive peak at \( H > 0 \) like those in the 5 mA curve in Fig. 1(a), but a negative peak at \( H < 0 \). Similarly, in the current scans of Fig. 3(b), the peak at \( H = 0.5 \) kOe is consistent with
FIG. 3: Data for sample 2. (a) $H$-dependence of $dV/dI$ at specified values of $I$, (b) $I$-dependence of $dV/dI$ at specified values of $H$. (c) Magnetization stability diagram extracted from $I$ scans such as shown in (b). Upward(downward) triangles: P→AP(AP→P) switching. A $H = -0.5$ kOe section shown with dashed line, (d) MR curves at $I = 8$ mA, at the specified in-plane angles between $H$ and the nominal easy axis of the nanopillar. AP, P denote the stability region of the respective configurations, P/AP is a bistable region. In (a),(b),(d), thick curves: scan from left to right, thin curves: scan in opposite direction, curves are offset for clarity.

those at $-0.7, 0.6$ kOe in Fig. 3(b), while the $-0.5$ kOe scan shows a small hysteresis in current switching with a negative peak at larger $I$. By comparing the 8 mA resistances to the left of the negative peak and to the right of the positive peak in Fig.3(a), we conclude that the negative peak corresponds to complete AP switching. The resistance increase to the right of the negative peak in Fig. 3(b) is consistent with the previously noted current-driven excitations in the P state [11]. Fig. 3(c) shows the stability diagrams extracted from $I$ scans such as those in Fig. 3(b), where we mark both the positive and negative peaks as reversible switching points. This plot clearly shows the asymmetry of behaviors with respect to reversal of $H$. For $H > 0$ the stability diagram is similar to those of Figs. 3(c,d). For $H < 0$ in Fig. 3(c), the reversible switching line has a positive slope, i.e. the negative peaks appear at decreasing $I$ as the magnitude of $H$ is increased. A dashed $H = -0.5$ kOe line crosses both a bistable region (hysteretic switching), and a reversible switching line. The positive slope of the reversible line is consistent with $\alpha + \beta < 0$, giving a negative peak in Eq. 4.

Fig. 3(d) shows $H$-scans at $I = 8$ mA with varied angles $\theta$ between the nominal easy nanopillar axis and $H$ directed in the sample plane. The $\theta = 0$ curve has a positive peak at $H > 0$ and negative peak at $H < 0$. The peaks in the $\theta = \pm 20^\circ$ curves are nearly symmetric, and positive for both directions of $H$. The $\theta = \pm 30^\circ$ curves are asymmetric again, and have double peaks for one of $H$ directions. These data show that the details of switching are sensitive to the sample shape defects, misalignment of the nanopillar easy axis with $H$, and are also affected by the Oersted field of the current and magnetization pinning. We note that only the last two factors (possibly in combination with the first two) give asymmetry between the behaviors at $H < 0$ and $H > 0$.

To summarize, we focused on four phenomena in Co/Cu/Co nanopillars at 295 K. First, we provided evidence (although not as clear as in Py/Cu/Py [11]) of a threshold current $I_t$ for excitations that occur in the reversible switching regime, but at lower $I$ than the reversible switching peak. Second, we showed that the sharp knee at $I = 0$, visible in a magnetization switching diagram obtained by fixing $I$ and varying $H$, is lost in a similar plot obtained by fixing $H$ and varying $I$. Third, we showed that the reversible switching peak shape can be derived from measurements of the variation of telegraph noise with $I$. Fourth, in Fig. 3 we showed an example of a switching diagram asymmetric in $H$, more complex than the symmetric one in Fig. 1. We attribute the complexity to a combination of sample shape asymmetry, the Oersted field, and possible misalignment of $H$. In particular interest in Fig. 3(b) is the negative peak, associated with re-entrance of the P state at high $I > 0$.

We acknowledge support from the MSU CFMR, CSM, the MSU Keck Microfabrication facility, the NSF through Grants DMR 02-02476, NSF-EU 98-09688, and NSF-EU 00-98803, and Seagate Technology.

[1] J. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996).
[2] F.J. Albert, J.A. Katine, R.A. Buhrman, and D.C. Ralph, Appl. Phys. Lett. 77, 3809 (2000).
[3] J.A. Katine, F.J. Albert, R.A. Buhrman, E.B. Myers, and D.C. Ralph, Phys. Rev. Lett. 84, 3149 (2000).
[4] F.J. Albert, N.C. Emley, E.B. Myers, D.C. Ralph, and R.A. Buhrman, Phys. Rev. Lett. 89, 226802 (2002).
[5] E.B. Myers, F.J. Albert, J.C. Sankey, E. Bonet, R.A. Buhrman, and D.C. Ralph, Phys. Rev. Lett. 89, 196801 (2002).
[6] F.B. Mancoff and S.E. Russek, IEEE trans. 38, 2853 (2002).
[7] J.Z. Sun, D. J. Munsma, T.S. Kuan, M.J. Rooks, D.W. Abraham, B. Ozyilmaz, A.D. Kent, and R.H. Koch, J. Appl. Phys. 93, 6859 (2003).
[8] J. Grollier, V. Cros, H. Jaffres, A. Hamzie, J.M. George, G. Faini, J. Ben Youssef, H. Le Gall, and A. Fert, Phys. Rev. B 67, 174402 (2003).
[9] B. Ozyilmaz, A.D. Kent, D. Monsma, J.Z. Sun, M.J. Rooks, and R.H. Koch, Phys. Rev. Lett. 91, 067203 (2003).

[10] S. Urazhdin, H. Kurt, W.P. Pratt, Jr., and J. Bass, Appl. Phys. Lett. 83, 114 (2003).

[11] S. Urazhdin, N.O. Birge, W.P. Pratt, Jr., and J. Bass, Phys. Rev. Lett. 91, 146803 (2003).

[12] S. Urazhdin, cond-mat/0308320

[13] If we follow the reversible switching peak to very large $I$ and $H$, the dwell times $\tau_P$ and $\tau_P$ extrapolate to values smaller than any plausible microscopic attempt time. At that point the magnetization dynamics no longer produce telegraph noise, but become more complicated.