Dynamics of magnetic domain wall motion after nucleation: Dependence on the wall energy

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The dynamics of magnetic domain wall motion in the FeNi layer of a FeNi/Al₂O₃/Cu trilayer has been investigated by a combination of x-ray magnetic circular dichroism, photoelectron emission microscopy, and a stroboscopic pump–probe technique. The nucleation of domains and subsequent expansion by domain wall motion in the FeNi layer during nanosecond-long magnetic field pulses was observed in the viscous regime up to the Walker limit field. We attribute an observed delay of domain expansion to the influence of the domain wall energy that acts against the domain expansion and that plays an important role when domains are small.

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Many of the fascinating phenomena in thin film magnetism that appear promising for new applications in magnetic data storage involve the use of multilayered magnetic systems, for example spin-valves and magnetic-tunnel-junctions. The study of the time dependence of the magnetic properties in multilayered systems is of high actual interest with respect to the achievable magnetic response time of such devices, but also from a fundamental point of view. It has been observed that the magnetization reversal for hard/soft magnetic trilayers is dominated by domain wall motion in quasi-static conditions and by the nucleation of many small domains in fast dynamic conditions. Such a difference in the reversal mechanism must obviously be accompanied by dramatic changes in the energetics, and magnetic domain walls will become much more influential at faster reversal rates.

The role of domain wall energy on the magnetization reversal is a long-debated issue. It has been discussed in the seventies in connection with bubble domains in perpendicularly magnetized materials. Malozemoff and Slonczewski pointed out that the domain wall energy leads to a wall curvature pressure that tends to contract the domain, thus confirming the domain collapse. Skomski et al., in a self-consistent magnetic-viscosity approach, pointed out a negative velocity for bubble domain expansion in small fields as consequence of the domain wall energy, which can amount up to several nanoseconds. This can be well described by an effective specific domain wall energy exerting a negative domain wall pressure when domains are small, just after nucleation, but becoming negligible once domains exceed a certain size.

In this Letter we present an experimental investigation of the influence of the domain wall energy on the magnetization reversal of the soft magnetic layer in magnetic tunnel junction-like trilayers. We study the reversal of the soft layer away from the magnetization direction of the hard layer. In this configuration the reversal is nucleation-dominated reversal for high fields, and a strong influence of the domain wall energy is expected. We use a stroboscopic pump–probe technique to observe in real space the repeated nucleation and expansion of domains and find that the influence of the domain wall energy leads to an apparent delay in domain nucleation, which can amount up to several nanoseconds. This can be well described by an effective specific domain wall energy exerting a negative domain wall pressure when domains are small, just after nucleation, but becoming negligible once domains exceed a certain size.

In in-plane domains there is no stabilizing demagnetizing energy as in perpendicular bubble domains, and the domain wall energy $Pγd$ of a domain with perimeter length $P$ in a film of thickness $d$ can be described simply by an effective field $H_{wall} = γλ/(4μ₀MₛP)$ acting against the external field $H_{ext}$. Here $γ$ is an effective domain wall energy averaged over the perimeter of the domain, and $λ$ is a geometric factor describing the ratio between area and squared perimeter of the domain ($λ = 4π$ for a circular domain). Only if $H_{wall}$ is small enough so that the corresponding wall velocity can be...
neglected, domains are stable in static conditions. In our case both, the domain wall field and the effective field from the coupling between the two ferromagnetic layers in a trilayered structure, $H_{copl}$, oppose the externally applied field, so that the total effective field is

$$H_{tot} = H_{ext} - H_{copl} - \frac{\gamma \lambda}{4\mu_0 M_S P},$$  \hspace{1cm} (1)$$

and thus depends on $P$. We consider as measurable quantity the speed of perimeter expansion, $dP/dt$, which in turn will be a function of $H_{tot}$. We show that the resulting inhomogeneous non-linear differential equation for $P$ can well describe the observed apparent delay in reversible domain nucleation using a fixed value for $\gamma \lambda$, thus revealing the manifestation of the domain wall energy in the reversal dynamics.

The sample used in this study was a 4 nm Fe$_{20}$Ni$_{80}$/2.6 nm Al$_2$O$_3$/7 nm Co trilayer grown by RF sputtering on the step-bunched surface of a 6° miscut Si(111) crystal. Underneath the Co layer, 3 nm of CoO has been deposited to increase the coercivity of the Co layer. The FeNi layer has been capped by 3 nm of Al to prevent oxidation. Details of the thermal treatment leading to the creation of step-bunches are given in Ref. 11. According to quasi-static longitudinal Kerr effect experiments, the sample features uniaxial anisotropy along the step-bunches. The coercivities are 1 mT for the FeNi and 4.3 mT for the Co layers, and a Néel type coupling field $\mu_0 H_{copl}$ of 1.2 mT favors parallel alignment. Details of similar types of samples are shown in Refs. 3 1 3 1 1 2.

The experiment was performed using a combination of x-ray magnetic circular dichroism (XMCD), photoelectron emission microscopy (PEEM), and a stroboscopic pump–probe technique 11. Magnetic field pulses are periodically applied at 312.5 kHz by a coil made of Cu foil wrapped around the sample. The magnetic response is stroboscopically probed by XMCD-PEEM with the same frequency at a fixed phase delay with respect to the magnetic field pulses. The time resolution is given by the x-ray pulse width and the jitter of the electronics, and is estimated as 100 ps. The domain wall motion in the two ferromagnetic (FM) layers was observed separately by tuning the photon energy of circularly polarized x-rays to the Fe and Co $L_3$ absorption edges for addressing the FeNi and Co layer, respectively. Measurements were performed at the UE56/2-PGM2 beamline at BESSY in Berlin.

In Fig. 1 we show images of the nucleation of domains and their subsequent expansion in the FeNi layer, observed at an amplitude of the bipolar field pulses of 5.8 mT. The pulse shape is shown in Fig. 1 (e). The positive and negative parts have the same amplitude (5.8 mT) and length (47 ns). Figs. 1 (a), (b), (c), and (d) show the magnetic domain structures in the FeNi layer at different pump–probe delay times, 9, 19, 24 and 29 ns, respectively. The easy axis is parallel to the vertical direction in the images, and the black and white contours indicate the magnetization pointing down and up, respectively. The direction of the incoming x-rays with 30° grazing angle to the surface is also indicated in (d). The field of view is 120 µm.

Before applying the pulses, the two FM layers were magnetically saturated in the same direction by a 15 mT field pulse of 3 ms duration. The direction is indicated by the white arrow in Fig. 1 (d), and corresponds to black contrast. During the pump–probe experiments, the first, negative part of the pulse is in the same direction as the saturation, and was used to obtain the same starting condition for each pulse. The second, positive part is in the opposite direction (see (e)). The magnetization in the FeNi layer starts to reverse into the white direction during this second part of the pulse. The start of the positive part of the pulse is set to zero time. The plateau of the pulse starts at 9 ns, at which time one can see only some small fuzzy white splotches, probably due to magnetic domains that are blocked on surface defects (a). However, they do not expand with time, and are thus not regarded in the analysis. Some white domains become visible in (b), and, as time goes by, they get larger (c and d). To get sufficient statistics, millions of pulses were applied to acquire each image.

The areas of white domains in Fig. 1 (b), (c), and (d) are superimposed into (f) with different shades of grey, middle grey, light grey, and dark grey, respectively. The expansion of the domains by propagation of the domain walls is clearly seen. In this experiment, the magnetiza-
of the Co layer was not affected by the field pulses, i.e., it always showed the black contrast.

In Fig. 2 the average perimeter of the three domains indicated by arrows in Fig. 1(f) is plotted as a function of time for each amplitudes $H_{\text{pulse}}$ of the field. $\mu_0 H_{\text{ext}}$ is ranging from 5.62 to 6.81 mT. The perimeter $P$ is measured by an ellipse-fit to the domains with an error of about 10%. The three domains were nucleated for all amplitudes of the field pulses, and it was possible to measure $P$ before they merged with other surrounding domains. The start of the plateau is indicated by a vertical line in Fig. 2. Linear fits to the data (broken lines) indicate that the measured values for $P$ extended linearly with time for each field amplitude. However, the intersections to the time axis of these lines do not come to the same time for each amplitudes. However, the intersections of time for each amplitudes indicated by arrows in Fig. 1(f) is plotted as a function of the field pulses (6.70 mT and 6.81 mT) are not linear fit. The two data points with the highest amplitudes of the field pulses (6.70 mT and 6.81 mT) are not included in the linear fit, since the velocity seems to reach saturation at around 5.2 mT of $\mu_0(H_{\text{ext}} - H_{\text{cpl}})$. This saturation of velocity is due to the modification of the spin structure inside the domain wall above the so-called Walker limit field [13, 14].

For the analysis according to Eq. 1 we use the data of Fig. 2 to extract the dependence of $dP/dt$ on $H_{\text{tot}}$, where we assume $H_{\text{tot}} \approx H_{\text{ext}} - H_{\text{cpl}}$ for large domains. The negative contribution of $H_{\text{wall}}$ to $H_{\text{tot}}$ for small domains makes it necessary to extend the velocity data to the lower field range for the numerical evaluation of $P(t)$. We assumed thermally activated wall motion for lower $H_{\text{tot}}$ with perimeter extension velocity

$$v_P = v_{P,0} \exp\left(\frac{\mu_0 M_S H_{\text{tot}} V_B - E_p}{k_B T}\right),$$

(2)

where $V_B$ and $E_p$ are the Barkhausen volume and the barrier energy, respectively [12, 16], and $\mu_0 M_S = 1$ T for FeNi. To provide a smooth transition to the experimentally determined regime of viscous motion at $H^* = 4.4$ mT, values of $V_B = (1.2 \pm 0.1) \times 10^{-23}$ m$^3$ and $E_p = (2.6 \pm 0.4) \times 10^{-20}$ J [16] have to be used (solid line in Fig. 3), while $v_{P,0}$ of 55 nm/ns [17]. At $H_{\text{tot}} > 5.2$ mT, a constant perimeter expansion speed of 9.3 $\mu$m/ns was assumed in order to match the two data points at 6.70 and 6.81 mT.

The perimeter extension was numerically evaluated according to Eq. 1 with 1 ps time increments and is plotted in Fig. 2 by solid curves. The best agreement was obtained for $P(t = 0) = 1.9 \mu$m and $\gamma \lambda = 9$ mJ/m$^2$. The simulation fits quite well to the experimental data. $P(t = 0)$ and $\gamma \lambda$ are found to be correlated by $\gamma \lambda = 3 \times 10^4$ (mJ/m$^3$) $P(t = 0) + 3.2$ (mJ/m$^2$), and no significant worsening of the fit is observed for values of $\gamma \lambda$ between 7 and 11 mJ/m$^2$, if $P(t = 0)$ is changed accordingly and kept within 3% of the respective value. It is seen that a deviation from the linear behavior occurs at the initial stages of domain expansion, thus leading to the observed apparent delay. For higher $\mu_0 H_{\text{ext}}$ (6.70 mT and 6.81 mT), $P$ starts to expand already on the rising slope of the pulse before 9 ns, as was also observed.
in the experiment. The above simulation assumed that there is no real delay in domain nucleation. Since the grey scale contrasts obtained in a static experiment were identical to the ones of the images obtained in the above experiment, the reproducibility of domain nucleation is close to 100%. Once the domains were visible, we did not observe an increase of the number of domains during the field pulses. This indicates that the domains were always nucleated as soon as the pulse field reached a certain threshold. The observation of a reproducible nucleation of domains at certain locations of the sample means that topographic features act as nucleation centers, and that the nucleation process is not thermally activated. Reproducible nucleation takes place at those positions where the local nucleation barrier is lower than the effective field. The increase of the number of nucleated domains with increasing pulse height indicates therefore a distribution of barrier heights.

We have assumed a constant elliptical shape for the domains with aspect ratio 1:4, thus λ ∼ 24. The perimeter speed can be converted into a domain wall speed along the easy axis of magnetization. This is plotted on the right axis of Fig. 2. The mobility of viscous domain wall motion along the easy axis is then 1600 m/(s mT) ± 10%. The initial P of 1.9 µm means that the width of the nucleation centers is around 0.19 µm, which is too small to be seen in the images, the lateral resolution of which was set to ∼ 1 µm for these measurements. The maximum speed of 2000 m/s along the easy axis is an order of magnitude larger that the value found for narrow permalloy lines using similar field values, indicating that it might be possible to increase this speed by an appropriate shaping of the wires [19].

The Walker limit field is given by μ₀H_{walker} = 1/2αµ₀M_r [13]. For Fe_{20}Ni_{80}, a value α = 0.01 is often used in the literature for the damping constant [17][21]. With this value, μ₀H_{walker} would be 5 mT. This is in good agreement with our experimentally obtained value of 5.2 mT.

The constant effective domain wall energy γ = 0.38 mJ/m² that was used for the simulation includes exchange and anisotropy energy inside the wall, magnetostatic contributions from the sharp ends of the elliptic domains, as well as repulsion of the long sections of the magnetic domain walls [22]. A refined model should take into account the dependence of γ on P. Since in the simulation γ contributes mainly when domains are small, deviations in the shape of the domains may also play a role when comparing the value for γ to an estimate for the wall energy of an isolated Néel type wall, which leads to a much higher value of 2.3 mJ/m² [23].

In conclusion, the reproducible nucleation of domains in the soft layer of a tunnel junction-like trilayer and the subsequent domain growth by domain wall propagation in the viscous regime and up to the Walker limit field is significantly influenced by the energy of magnetic domain walls. This leads to an apparent delay of domain expansion. A faster magnetization reversal, which is required for the coming magnetic recording devices, is drastically hindered by this magnetic domain wall energy when magnetic domains are small. By analogy, the techniques and results shown in this work are equally applicable to other nucleation and growth phenomena like crystallographic phase changes, superconducting transitions, and solidification theory.

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\[ \sqrt{AM^2/(2\mu_0)} = 2.3 \text{ mJ/m}^2 \text{ for } A = 1.3 \times 10^{-11} \text{ J/m}. \]