AC-polarized neutron reflectometry:
Application to domain dynamics in thin Fe film

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Abstract. We report on the first application of polarized neutron reflectometry (PNR) to probe the re-magnetization kinetics in thin films subjected to periodic magnetic fields. Specular PNR and off-specular scattering were recorded from a 100 nm thick MBE grown Fe film under the application of AC magnetic fields with amplitudes up to 60 Oe and frequencies in the range of 0.3 - 1.8 MHz. It was found that up to 0.4 MHz a complete magnetization reversal of the Fe film takes place during each AC field cycle. Higher frequencies cause only a partial re-magnetization and above 0.8 MHz the AC field no longer alters the sample magnetization. High frequencies suppress magnetization fluctuations on a micrometer scale which are otherwise seen via off-specular scattering.

1. Introduction
Domain wall (DW) propagation in magnetic films and nanowires is presently a highly active field due to potential applications in magnetic storage media, such as the concept of a "Racetrack Memory" [1]. Three regimes can usually be distinguished. For low fields up to a critical value, the DW velocity increases linearly with the applied field. In this region the DW motion is viscous and the type of DW does not change during propagation. However, beyond a critical magnetic field, which is known as the Walker break down field [2], the DW speed rapidly decreases because of a new damping mechanisms and the transformation into different types of domain walls. DW motion in films and nanowires has been studied by various methods in recent years, such as by magnetoresistance [3], magnetic force microscopy [4], spin scanning electron microscopy (S-SEM) [5], and magneto-optics [6, 7]. Here we present a new method to probe the dynamics of magnetic domains in an AC magnetic field covering the range of magnetization reversal times down to fraction of a microsecond using polarized neutron reflectometry (AC-PNR). Most of the methods mentioned above work in direct space and time, providing images of propagating domain walls in magnetic nanowires. AC-PNR is a reciprocal space method, which has the advantage that it can measure the time evolution of magnetization depth profiles averaged over the sample surface.

2. Experimental procedures
The experimental geometry realized with the polarized neutron reflectometer ADAM at the Institut Laue Langevin[8](ILL, France) is sketched in Fig. 1. An AC magnetic field $H_{AC}(t) =$
Figure 1. Scheme of the experiment. AC and bias DC field, as well as domain magnetization (red arrows), are collinear with polarization direction (blue arrows through "balls") which is normal to the scattering plane. The latter contains incoming, $\mathbf{k}_i$, outgoing, $\mathbf{k}_f$, wave vectors and the wave vector transfer $\mathbf{Q}$. Red ellipses denote cross sections of the coherence ellipsoids with the sample surface. Specular reflection and off specular scattering intensity is a result of incoherent averaging over a number of those ellipsoids covering the whole surface (see for details Ref.[9]).

$H_0 \cos(2\pi ft)$ with frequencies $f = 0.3 – 1.8$ MHz was applied along one of the easy axis ($Y$-axis) within the film plane and perpendicular to the specular wave vector transfer $\mathbf{Q}$. AC field amplitudes $H_0$ up to 60 Oe were applied to surely overcome the coercive field $H_c = 21$ Oe. In order to fix the initial saturated state of the sample, a bias field of $H_b = 25$ Oe was applied in addition to the AC field.

Two non-spin-flip (NSF) $R^{\pm \pm}$, and two spin-flip (SF), $R^{\pm \mp}$, reflectivities were recorded for $f = 0.3, 0.6$ and 1.5 MHz. A representative example for a set of data taken at $f=0.3$ MHz together with results of a model fit is depicted in Fig. 2. Data on specular reflection and off-specular diffuse scattering were collected at $f = 0, 0.3, 0.45, 0.6, 0.8, 1.0$ and 1.8 MHz with a position sensitive detector (PSD) for a polarized incident neutron beam but without polarization analysis of the scattered beam. Intensity maps arranged into $R^+$ and $R^-$ panels are shown in Fig. 4(a,b), where the specular reflection ridge along the diagonal and diffuse scattering spots beside the ridge can be recognized. Recording AC-PNR data requires a special set-up, including a RF generator, amplifier, wide band transformer, and a resonance circuit allowing to vary amplitude and frequency of the periodic magnetic field over a wide range. The details of the set-up will be published elsewhere [10].

3. Experimental results

According to Fig. 2, in an AC field of 0.3 MHz the NSF reflectivities $R^{++}$ and $R^{--}$ are split above the angle of the total reflection. Hence, the sample magnetization averaged over the AC field period $T = 0.3$ microseconds is not zero. At the same time, each of NSF reflectivities reveal critical edges of total reflection for both spin components and hence the sample is not saturated. Weak SF reflectivity in Fig. 2 indicates small deviations of the magnetization vector from the applied field direction. Splitting between $R^+$ and $R^-$ NSF reflectivities is also seen in Fig. 4. The $R^+$, $R^-$-splitting significantly increases with increasing frequency and reaches a maximum value above $f = 0.8$ MHz. Simultaneously, the off-specular scattering becomes strongly asymmetric and then vanishes at 1.8 MHz. No splitting in the NSF reflectivities (see Fig. 3) and no asymmetry in the off-specular scattering is present if bias field is $H_b = 0$.

4. Discussion and conclusion

The experimental observations may quantitatively be described in a simplified scenario of remagnetization driven by 180° DW propagation: DWs nucleated at the sample edges and/or
in the bulk propagate along the X-axis against each other, erasing unfavorable domains. The DW’s may start to move at the time moment \( t = t_0 \) (see, Fig. 5) at which \( H(t_0) \approx -H_c \). If a field variation is so slow that \( H(t) \leq -H_c \) during DWs propagation till they merge somewhere in the sample and annihilate, then reversal takes place. After reversal, the sample may stay in a negative saturation till \( t = t_2 \) at which \( H(t_2) \approx +H_c \). Then the process is reversed: DWs are again nucleated and propagate back completing the re-magnetization cycle. At \( H_b = 0 \) remagnetization in both directions should proceed over the same time span, while for \( H_b \neq 0 \) the sample may, on average, be preferentially magnetized in one direction. The fraction of the period spent in one of the saturated states can readily be deduced via fitting the data to the incoherent sum of reflection coefficients for two magnetized states weighted with the corresponding fraction of the period. The latter is plotted in Fig. 6 against the frequency at two values of the AC field amplitudes \( H_0 = 60 \text{ Oe} \) and \( H_0 = 55 \text{ Oe} \). From Fig. 6 it follows that for \( f < 0.4 \text{ MHz} \) the fraction of the period well coincides with that expected from the ratio between \( H_b \) and \( H_0 \). However, at elevated frequencies this fraction decreases and finally vanishes at \( f \sim 1.5 \text{ MHz} \). At high frequencies DWs do not succeed to pass all the way till annihilation before the moment of time \( t = t_4 \) at which the increasing external field reaches the value \( H(t_4) \approx -H_c \). Then the reversal process is terminated until the moment of time \( t = t_2 \). After that the DWs propagate

Figure 2. SF and NSF specular reflectivities measured (points) at \( f = 0.3 \text{ MHz} \) and \( H_b = 25 \text{ Oe} \) fitted (lines) to the model of a partially magnetized state.

Figure 3. Specular reflectivities \( R^+ = R^- \) at \( f = 0.3 \text{ and } 0.6 \text{ MHz} \), \( H_0 = 60 \text{ Oe} \) and \( H_b = 0 \): The sample is in the totally demagnetized state.

Figure 4. Scattering maps \( R^- \) (left) and \( R^+ \) (right) recorded for 0.3 MHz (top panel) and 1.8 MHz (bottom panel). Here the AC field amplitude is \( H_0 = 60 \text{ Oe} \), the bias field is \( H_b = 25 \text{ Oe} \). Specular reflection is represented by ridges running along the lines with equal angles \( \alpha_i = \alpha_f \) of incidence and scattering. The off-specular scattering seen bulging out near specular ridges is strongly asymmetric at high frequency.
back restoring initial saturation state where the sample spends a certain amount of time before the next cycle starts. The lowest frequency at which the magnetization reversal is no longer complete allows to estimate the time for DW nucleation. For the present sample this is on the order of 0.5 microseconds. So far we can only determine the re-magnetization rate of the sample, but not the DW velocity. This requires to know how far during one cycle. Our results strongly indicate that the distance is bigger than the neutron coherence length which is estimated to be of about 100 micrometers. This gives a lower limit for the mean DW velocity of 30 m/sec. More accurate determination of the DW velocities will, however, be possible in forthcoming experiments with time resolved PNR analysis synchronized with the AC field. Such experiments should also shed more light on the nature of the off-specular scattering seen in Fig. 4, which may result from magnetic inhomogeneities (DW nucleation centers, residual domains, spin waves, etc.). At present we can only infer from our simulations of the off-specular maps that the residual magnetic domains are about 1500 nm in size and that the magnetization direction is randomly tilted by a few degrees against the applied field. Those magnetic inhomogeneities are still detectable above the saturation field, but vanish at high frequencies, or in static fields \(H \geq 120\) Oe.

![Figure 5.](image-url) Variation of the AC field amplitude during one period.

![Figure 6.](image-url) Dependence of the fraction of the initial state magnetization on the frequency for field amplitudes \(H_0 = 55\) and \(H_0 = 60\) Oe.

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