Domain wall dynamics of periodic magnetic domain patterns in Co$_2$MnGe-Heusler microstripes

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Keywords: domain wall dynamics, domain wall mobility, magnetic anisotropy, domain structure, Heusler alloy, ac-MOKE susceptometer

Abstract

Highly symmetric periodic domain patterns were obtained in Co$_2$MnGe-Heusler microstripes as a result of the competition between growth-induced in-plane magnetic anisotropy and shape anisotropy. Zero field magnetic configurations and magnetic field-induced domain wall (DW) motion were studied by magnetic force microscopy-image technique for two different cases: dominant uniaxial- and dominant cubic in-plane anisotropy. We implemented a magneto-optical Kerr effect susceptometer to investigate the DW dynamics of periodic domain structures by measuring the in-phase and out-of-phase components of the Kerr signal as a function of magnetic field frequency and amplitude. The DW dynamics for fields applied transversally to the long stripe axis was found to be dominated by viscous slide motion. We used the inherent symmetry/periodicity properties of the magnetic domain structure to fit the experimental results with a theoretical model allowing to extract the DW mobility for the case of transverse DWs ($\mu_{TDW} = 1.1 \text{ m s}^{-1} \text{ Oe}^{-1}$) as well as for vortex-like DWs ($\mu_{VDW} = 8.7 \text{ m s}^{-1} \text{ Oe}^{-1}$). Internal spin structure transformations may cause a reduction of DW mobility in TDWs as observed by OMMFF simulations.

1. Introduction

Domain wall (DW) propagation in laterally patterned magnetic thin films holds promise for both fundamental interest and potential for technological applications. Fundamentally, DW motion can be induced by external magnetic fields or by spin polarized currents [1–8]. A significant part of measurements with injected spin polarized current have been done on systems with the magnetization direction in-plane. In nanostripes with in-plane magnetization, two DW types have been identified: in thin and narrow stripes, transverse walls (TDWs) are energetically favored, while in thicker and wider stripes vortex-like walls (VDWs) have lower energy [9, 10]. The advantage of these systems are broad DWs which are less sensitive to pinning. Spin-transfer torque driven DWs in nanosized permalloy (Py = Ni$_{81}$Fe$_{19}$)-wires nowadays are the basis for the racetrack memory concept development at IBM’s Almaden Research Center [11]. However, very high spin-current densities are still required to induce a DW displacement. Py has been the material of choice in the scientific community for the investigation of DW propagation, as it possesses negligible magnetocrystalline anisotropy and low damping. However, materials with low damping are more sensitive to undergo DW spin structure modifications, which can have marked effects on the DW dynamics since both DW velocity and DW pinning are sensitive to the DW spin structure [6, 8].

A key parameter for characterizing magnetic DW motion is the DW mobility ($\mu_{DW}$), which describes the rate of change of wall velocity ($v_{DW}$) with variation of the external field. Schryer and Walker [12] derived a 1D model from the Landau–Lifshitz–Gilbert equation, which has been the basis for subsequent additional works [13, 14]. These models describe the fundamental aspects of DW dynamics with three characteristic regimes: at low fields, the equation of motion give an exact stationary-state solution characterized by a linear dependence of the velocity on the applied field. In this case the mobility is given by $\mu_{DW} = \gamma \Delta / \alpha$, where $\gamma$ is the gyromagnetic...
Prior to lateral patterning, the Co$_2$MnGe thin films were magnetically characterized by rotational MOKE and commercial Co–Cr MFM tips. The dynamic responses of magnetic DWs were studied by recording the in-plane X and out-of-plane Y components as a function of field amplitude $H_0$ and driving frequency $f$ by using an ac-MOKE susceptometer. This is an extension of a standard MOKE setup consisting of a diode-laser, polarizing and analyzing optics (Glan–Thompson prisms), a high-speed silicon photo-diode, and lock-in amplifier [34]. The ac magnetic field is generated by Helmholtz coils. A second lock-in amplifier is used as a generator providing a maximum field amplitude of 8.6 mT with driving frequency varying from 0.5 Hz to 150 Hz. The Kerr signal ($V_{\text{Kerr}}$) is measured by lock-in amplification of the photo-diode output.

2. Experimental

Arrays containing $510 \times 90$ elements of flat rectangular stripes of width $w = 2.5 \, \mu m$ and length $L = 20 \, \mu m$ were fabricated from 60 nm thick textured Co$_2$MnGe thin films. The films were prepared by rf-sputtering from a Heusler alloy target with stoichiometric composition on $a$-plane Al$_2$O$_3$-substrates. Prior to the Co$_2$MnGe film growth and in order to induce a high-quality (110) textured growth of the Heusler phase, a 2 nm thick vanadium seed layer was deposited. Films were finally protected against oxidation with a 5 nm thick Al$_2$O$_3$ capping layer. Magnetic investigations of the films were carried out by using magneto optical Kerr effect (MOKE) and superconducting quantum interference device magnetometer. Longitudinal MOKE hysteresis loops were taken as a function of the in-plane azimuthal angle $\varphi$ of the applied magnetic field, where $\varphi = 0$ is parallel to the in-plane $c$-direction of the $a$-plane Al$_2$O$_3$ substrate. The stripe arrays were fabricated using electron-beam lithography, lift-off techniques and ion beam etching. The magnetic microstructure was investigated at room temperature by magnetic force microscopy (MFM) at a lift scan height of 100 nm by using a multi-mode microscope (NT-MDT) and commercial Co–Cr MFM tips.

The dynamic responses of magnetic DWs was studied by recording the in-phase $X$ and out-of-phase $Y$ components as a function of field amplitude $H_0$ and driving frequency $f$ by using an ac-MOKE susceptometer. This is an extension of a standard MOKE setup consisting of a diode-laser, polarizing and analyzing optics (Glan–Thompson prisms), a high-speed silicon photo-diode, and lock-in amplifier [34]. The ac magnetic field is generated by Helmholtz coils. A second lock-in amplifier is used as a generator providing a maximum field amplitude of 8.6 mT with driving frequency varying from 0.5 Hz to 150 Hz. The Kerr signal ($V_{\text{Kerr}}$) is measured by lock-in amplification of the photo-diode output.

3. Results and discussion

3.1. Thin films: angular dependence of the coercivity

Prior to lateral patterning, the Co$_2$MnGe thin films were magnetically characterized by rotational MOKE technique to determine the in-plane magnetic anisotropy. As previously reported, the effective in-plane magnetic anisotropy for Co$_2$MnGe thin films grown on $a$-plane Al$_2$O$_3$ can be described by a superposition of a fourfold and a uniaxial anisotropy term [29]. The magnitude of the twofold and fourfold anisotropy constants...
depends on the growth conditions and can vary appreciably. The microscopic origin for these variations is presently not clear. However, the large scattering of the anisotropy parameters is a characteristic feature of Heusler thin films \[17\]. The substrate miscut and the specific substrate surface conditions have an important influence.

In the present work, we focus on two different anisotropy properties represented by two samples denominated A and B. These two samples are distinguished by their in-plane magneto-crystalline anisotropies, which are controlled by the growth conditions, in particular by the growth temperature and magnetic field-assisted deposition. Figures 1(a) and (b) show the polar plots of the coercive field \(H_c(\phi)\), measured as a function of the azimuthal angle \(\phi\) at room temperature of samples A and B, respectively. Regarding sample A, a two-fold symmetry can clearly be recognized confirming the dominant uniaxial nature of the in-plane magnetic anisotropy with an easy axis at \(\phi = 0\), which is aligned with the \(c\)-axis of the \(\text{Al}_2\text{O}_3\) substrate. The magneto-crystalline anisotropy constant \(K_U\) given by \(\frac{1}{2}(H_U M_K)\) was determined to be \(4.1 \times 10^3\) J m\(^{-3}\), considering a saturation magnetization \(M_K = 6.3 \times 10^5\) A m\(^{-1}\) and an anisotropy field \(H_U = 13\) mT as obtained by magnetization measurements with the field applied perpendicular to the \(c\)-axis. By contrast, the polar plot of the coercive field of sample B evidences a four-fold symmetry of the in-plane anisotropy with two easy axes aligned parallel and perpendicular to the \(c\)-axis of \(\text{Al}_2\text{O}_3\). For the latter case, the strength of the fourfold in-plane anisotropy is estimated to be \(K_u = 2.7 \times 10^3\) J m\(^{-3}\).

We used these two different symmetries of the in-plane anisotropy for the study of magnetic domain structures in microstripes. In the following, we present both equilibrium domain structures and dc-magnetic field-induced DW motion for the lateral patterned samples A and B.

### 3.2. Domain structure in microstripes

By means of e-beam lithography, arrays of stripes were fabricated with a width \(w = 2.5\) µm and lengths \(L = 20\) µm oriented perpendicular to the magnetic easy axis. Distances between the stripes are \(5\) µm and \(10\) µm along the short- and long-axis of the stripes, respectively; which are large enough to suppress magnetostatic interactions between stripes. Figures 2(a) and (b) present MFM images and simulated domain structure (using the object oriented micromagnetic simulation package OOMMF \[35\]) of individual stripes prepared from samples A and B, respectively; the arrows indicate the magnetization directions. Prior to recording the images at zero field, the stripes were magnetically saturated along the magnetic easy axis. In the case of the sample A with dominant in-plane uniaxial anisotropy, competing magnetostatic, magneto-crystalline and exchange interactions result in a regularly symmetric stripe domain configuration with a well-defined domain size \[29\]. Domains with the magnetization direction perpendicular to the stripe long axis are mostly separated by \(180^\circ\) transverse DWs. The domain size \(\delta\) parallel to the stripe long axis is highly regular and has an average value of \(\delta_{\text{TDW}} = 1.8 \pm 0.2\) µm. In contrast, in case of microstripes from sample B, the dominant cubic anisotropy favors the magnetization to lie along as well as perpendicular to the long axis of the stripes; as a result, the magnetization is organized into a diamond-type domain structure as observed in the MFM contrast and OMMF simulations.

![Figure 1](image1.png)

**Figure 1.** Polar plots of coercive field \(H_c(\phi)\) of sample A (a) and sample B (b) as a function of the azimuthal angle \(\phi\); \(\phi = 0\) denotes the angle of the magnetic field direction aligned with the crystallographic \(c\)-axis of the \(\text{Al}_2\text{O}_3\) \(a\)-plane substrate.
shown in figure 2(b). This system is termed as containing vortex-like DWs or VDWs. The lateral domain length along the stripe axis is $\delta_{VDW} = 2.3 \pm 0.2 \mu m$.

3.3. dc-magnetic field-induced DW motion

3.3.1. Stripe domain structure (sample A)

When a dc magnetic field is applied in the direction transverse to the stripe long axis, the stripe domain structure (in figure 2(a)) responds as illustrated by the MFM images in figure 3(a): the principal effect of applying the field in that direction is to initiate a DW motion in the direction perpendicular to the field. The sideways DW displacement depends on the field strength; by increasing the field amplitude progressively from $H_1 = 2.5$ mT to $H_2 = 4.5$ mT, DWs displace further (label II). However, this motion may occur only until the maximum distance $D/2$ is reached, where $D$ is the domain size. Once the magnetic field reaches the annihilation field ($\mu_0 H_{an} = 6.4$ mT), DWs synchronously disappear and the magnetization approaches saturation. In magnetic saturation a transverse single domain state is observed (label III). According to the latter, applying a dc field transversally to the stripe long axis leads to both a regular sideways motion of $180^\circ$ DWs and a synchronic DW annihilation.

3.3.2. Diamond-like domain structure (sample B)

Similar to the stripe domain case above, by applying a field in the direction transverse to the stripe long axis, the diamond-like structure responds by DW motion. A simplified way to describe the DW motion in this case is by an effective translational displacement of the vortex core along the stripe long axis, as schematically shown in figure 3(b) for the fields $H_1 = 1.2$ mT and $H_2 = 2.0$ mT (label II). The sideways vortex core displacement is also limited by $D/2$; once this length is reached, adjacent domains coalesce and the magnetization approaches saturation (label-III). From static MOKE hysteresis loop measurements (not shown) and MFM observations, the annihilation field was obtained as $\mu_0 H_{an} = 3.2$ mT.

3.4. DW dynamics of periodic magnetic domain structures

DW dynamics of the periodic domain structures shown in figure 2 were investigated by applying an ac-magnetic field in the same direction as for the dc-magnetic field (transverse to the stripe long axis). According to the results reported in section 3.3 it can be expected that the domain structures, when exposed to an ac-field $H(H_0, f)$, will exhibit an alternating sideways DW motion along the stripe long-axis (see the animations of MFM images in supplementary videos for TDWs and VDWs cases). In this case, the amplitude of the DW displacement depends on both $f$ and $H_0$. The implemented ac-MOKE susceptometer allows for recording the in-phase ($X$) and out-of-phase ($Y$) components of the Kerr signal as a function of $f$ and $H_0$. MOKE experiments were carried out at room temperature by varying the frequency in a range of $0.5$ Hz $< f < 100$ Hz and the amplitude in a range of $0.4$ mT $< \mu_0 H_0 < 8.8$ mT.
For sideways DW slide motion in a regular magnetic stripe pattern, Kataja and van Dijken in [15] derived analytical expressions (see equation (1)) to describe the normalized $X_n$ and $Y_n$ components as a function of the frequency $f$ and field amplitude $H_0$ as:

$$X_n = 0,$$

$$Y_n = \frac{1}{f} \left[ \frac{1}{\sqrt{2\pi D}} \mu_{DW} (H_0 - H_d) \sqrt{1 - \frac{H_d}{H_0}} \right] = \frac{1}{f} \left\{ T \left( H_0 \right) \right\}. \quad (1)$$

According to these expressions, while the in-phase component in the slide regime vanishes, the $Y_n$ component shows a dependence on both amplitude and frequency of the applied field. Moreover, it contains terms combining the depinning field $H_d$ and the DW mobility $\mu_{DW}$. Experimentally, we first measured the frequency dependence of $X$ and $Y$ for a constant value of $H_0$. Figure 4 shows the $X$ and $Y$ components of the measured Kerr signal versus frequency at $\mu_0 H_0 = 4.0$ mT for stripe array of sample A. The response of the system for this field amplitude can be divided into three dynamic regimes: at high driving frequencies,
Figure 4. Normalized in-phase ($X_n$) and out-of-phase ($Y_n$) components of the Kerr signal of sample A as a function of the driving frequency keeping the field amplitude $H_0 = 4.0$ mT. Three different dynamic regimes can be recognized (refer to text). Inset: evolution of the $Y_n$ signal by varying the field amplitude from 1.3 mT to 5.0 mT.

$f > 70$ Hz, no MOKE signal is detected, i.e. both $X$ and $Y$ components nearly vanish; in this frequency regime DWs remain pinned. As soon as the frequency reaches a value around 70 Hz, the out-of-phase component ($Y_n$) starts to increase, marking the depinning frequency $f_d$ at which the oscillatory and viscous slide motion of the existing DWs sets in. With decreasing frequency the amplitude of wall displacement grows, thus the imaginary field amplitude from 1.3 mT to 5.0 mT. Figure 5 shows the $Y_n$-component versus frequency measured at different field amplitudes. The solid lines in this plot are fits to the experimental data using equation (1). The orange solid line in this graph is a fit to the experimental data for the TDW-system; we thus obtain $\mu H = 0.47$ mT, and a DW mobility of $\mu_{DW} = 1.1 \text{ m s}^{-1} \text{ Oe}^{-1}$. Following the same procedure for the case of VDW-system (pink solid line), we obtain a depinning field of $\mu H = 0.98$ mT and a DW mobility of $\mu_{DW} = 8.7 \text{ m s}^{-1} \text{ Oe}^{-1}$. Similar values for the DW mobility have been reported for Ho-doped Py wires [8]. According to our results, the vortex-like DW-system responds faster to the applied field, exhibiting a DW mobility about seven times larger than the TDW-system.

It is well known that DW dynamics is sensitive to the internal DW structure. The DW internal structure depends on the thickness, width and material parameters of the constituting magnetic nanostructure [9, 10, 36]. According to analytical models [12, 14], the DW mobility depends directly on the DW width; since vortex-like DWs exist for larger widths, one could expect higher mobility for a vortex wall. Moreover, numerical calculations [37] indicate that transverse and vortex walls behave differently. Numerical results of DW mobility as a function of wire widths confirm that the mobility behavior of TDWs approximates the 1D model quite well, while VDWs are characterized by a drastic increase of DW mobility deviating strongly from this theoretical prediction. These analytical as well as numerical calculations support our experimental observation for Co$_2$MnGe stripes that VDWs can move faster than TDWs.

One possible reason for the observed low mobility of TDWs compared to the VDWs may be related to changes of the DW internal spin structure as reported in [6] and [8]. In their work the authors deduced a direct correspondence between the magnitude of damping constant $\alpha$ and the rigidity of DWs. For small $\alpha$ the DW.
Figure 5. (a) Plot of $Y_n$ as a function of $1/f$, (b) DW mobility $\mu_{DW}$ and depinning field $\mu_0 H_d$ extracted from the fit to the experimental data $T(H_0)$ versus $H_0$ for transverse DWs (orange and green) and vortex-like DWs (pink and purple).

Figure 6. OOMMF simulations of field driven DW motion which evidence a reconfiguration of the internal DW spin structure via nucleation of additional flux-closure structures.
spin structure undergoes periodic distortions that lead to a reduction of the mobility. Motivated by these results, we searched for possible modifications in the DW structure of TDW and performed micromagnetic simulations in order to reveal the evolution of the spin structure of the TDW-system when increasing the external field.

Figure 6 shows OOMMF simulations of the spin structure in a stripe of the same dimensions as the experimental one ($t = 60 \text{ nm}$, $w = 2.5 \mu \text{m}$ and $L = 20 \mu \text{m}$). Simulations were performed for two different field amplitudes ($H_1$ and $H_2$) with $H_1 < H_{an}$ and $H_{an} > H_2 > H_1$.

Our OOMMF simulations indeed reveal that the transverse DWs are not completely transversal, but some kind of flux closure structures are formed. When the field is increased from $H_1$ to $H_2$, the DW structure changes from a two-vortex state into a three-vortex state, as highlighted in figure 6. Such kind of internal spin structure transformations may drive the DW mobility to slow down as observed for TDWs.

4. Conclusions

We have investigated the DW dynamics of periodic domain structures by using ac-MOKE techniques on Co$_2$MnGe-Heusler microstripes. The inherent symmetry/periodicity of the domain patterns allows an analysis of the experimental data using existing theoretical models for DW dynamics. The analysis of the in-phase and out-of-phase components of the Kerr signal obtained as a function of magnetic field frequency and amplitude revealed that DW dynamics is dominated by viscous slide DW motion. The quantitative analysis of the DW mobility for two different symmetries i.e. transverse DWs and vortex-like DWs give evidence that the wall mobility for VDWs is larger than for TDWs, in agreement with theoretical predictions. We report for the first time experimental values for the DW mobility in Co$_2$MnGe microstructures, and find that they are comparable with experimental values derived for Py. Since a high mobility of DWs is an important and desirable property in many spintronic devices, our results give further support for the potential of ferromagnetic Heusler half metals in the field of spintronics.

Acknowledgments

The authors would like to thank Sabine Erdt-Böhm, Peter Stauche and Dr Frank Brüssing for technical help and the SFB 491 as well as the state of NRW for financial support of the e-beam lithography and MFM facilities. One of us (KG) gratefully acknowledges financial support through DAAD and UNESCO/L’Oreál fellowships.

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