Journal of Magnetism and Magnetic Materials 323 (2011) 1501–1508

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Complex anisotropy and magnetization reversal on stepped surfaces probed by the magneto-optical Kerr effect

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ARTICLE INFO

Article history:
Received 21 October 2010
Available online 19 January 2011

Keywords:
Fe thin films
Stepped surfaces, vicinal surfaces
Magnetic anisotropy
Magneto-optical Kerr effect

ABSTRACT

So-called split hysteresis loops have been measured for ultrathin ferromagnetic films grown on stepped surfaces. Since the shape of the loops is sensitive to the direction in which the magnetic field is applied with respect to the steps, the sample orientation against the field is particularly important. We performed systematic magneto-optical Kerr effect studies for 15 and 58 ML of Fe grown on Au(1,1,13). In view of the complex magnetic anisotropy of such systems we discuss representative hysteresis loops taken at sample orientations misaligned from the field (and laser beam) direction. In particular, the presence of a so-called low field component to the hysteresis loops is discussed and its reversed polarity is explained.

1. Introduction

In thin ferromagnetic (FM) films grown on stepped surfaces, magnetic anisotropy can be modified in comparison to the anisotropy of films grown on atomically flat surfaces [1–3]. Such a modification is often described as an additional uniaxial anisotropy with the easy magnetization axis in the film plane, usually oriented along the step direction. It can happen, however, that the easy magnetization axis is oriented perpendicular to the steps, in particular below a certain thickness [4,5] or for some film/substrate combinations above a certain film thickness [2]. In case the steps are oriented along one of the easy axes of the four-fold anisotropy of a FM film, one of them becomes the easy magnetization axis [6]. The other becomes the intermediate magnetization axis because it combines the easy character of the four-fold anisotropy with the hard character of the uniaxial anisotropy.

The uniaxial contribution to the anisotropy can oscillate due to quantum well states (QWS) which can form in FM thin films and alter the magnetic anisotropy strongly [7,8]. Such quantum oscillations of magnetic anisotropy have been discovered in Fe films grown on stepped surfaces of Ag(0 0 1) such as Fe/Ag(1,1,10) [4] and Fe/Ag(1,1,6) [5] systems.

Due to the uniaxial contribution to the anisotropy, so-called split hysteresis loops can be measured, when the magnetic field is applied along the intermediate magnetization axis. The split hysteresis loops are characterized by a shift field (H_s) being defined as half of the distance between two constituent loops [1]. For many years, split hysteresis loops have been used successfully to tackle many problems in magnetic anisotropy [9–11]. In particular, in the case of oscillatory magnetic anisotropy, split hysteresis loop have proven to be an invaluable tool [4,5,12]. Detailed evaluation of the split hysteresis loops makes it possible to determine both the oscillation period and the oscillation amplitude of anisotropy oscillations [4,5]. Therefore, a proper understanding of the split hysteresis loops is very important.

Principally speaking there should be no difference between the hysteresis loops measured along the intermediate magnetization axis, whether the easy magnetization axis is oriented parallel or perpendicular to the steps. However, the measured split hysteresis loops are not exactly equivalent. Assuming that the magnetization is aligned in the sample plane and oriented along the easy magnetization axis, the split hysteresis loops (measured along the intermediate magnetization direction) should show zero signal in remanence. In reality, in particular if the easy magnetization axis is oriented perpendicular to the steps, the split hysteresis loops show additional features. The experiments are performed on ultrathin films grown and analyzed under ultrahigh vacuum conditions (UHV), the hysteresis loops are measured by applying the magneto-optical Kerr effect (MOKE) [13,14]. At zero field the Kerr signal does not vanish and gives a remarkable contribution (or even a low field hysteresis loop) to the total Kerr hysteresis loop. Such low field features in split hysteresis loops were observed before, e.g. for Fe films grown on Ag(1,1,10) and attributed to "a small portion of out-of-plane magnetization" [4,5].

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doi:10.1016/j.jmmm.2011.01.008

In this article we report on hysteresis loops measured by MOKE for FM films grown on stepped surfaces. In particular, we show the influence of the magnetic anisotropy on the shape of the hysteresis loops. Systematic studies were performed for Fe films grown on Au(1,1,13) and compared to the hysteresis loops reported previously for Fe films grown on Ag(1,1,10) [4] and Ag(1,1,6) [5]. Hysteresis loops were probed under varying conditions, in particular with increasing misalignment to the intermediate magnetization axis. A detailed model explaining the shape of the hysteresis loops is proposed and discussed.

2. Model description

If the easy magnetization axis is oriented parallel to the steps, split hysteresis loops can be measured with the magnetic field applied perpendicular to the steps. Vice versa, split hysteresis loops can be measured along the steps if the easy magnetization axis is oriented perpendicular to the steps. Usually both cases are assumed to be equivalent. In the following sections we will discuss in detail the case of the easy magnetization axis oriented perpendicular to the steps, which will be finally compared to the case of the easy magnetization axis oriented along the steps.

In case the easy magnetization axis is oriented perpendicular to the steps, with the magnetic field applied along the steps and decreasing below H_s, the magnetization switches to the easy magnetization axis, i.e. it becomes oriented perpendicular to the steps. In absence of a field component perpendicular to the steps, i.e. when the external magnetic field is applied perfectly along the steps (i.e. at $\alpha_F = 0$) the transition of the magnetization from an orientation along the steps to an orientation perpendicular to the steps can proceed clockwise or counterclockwise. Therefore, at zero field the magnetization can be oriented perpendicular to the steps in positive or negative direction with equal probability. Consequently, there will be no net magnetization perpendicular to the steps.

In a real experiment the external magnetic field is usually applied at $\alpha_F \neq 0$. Therefore, there is also a field component which is applied perpendicular to the steps. With the magnetic field applied along the steps and decreasing below H_s, the magnetization switches perpendicular to the steps (i.e. to the easy magnetization axis) into the direction in which the field component perpendicular to the steps is applied. Moreover, the field component perpendicular to the steps affects the magnetization oriented perpendicular to the steps and switches it even if the field is vanishingly small (see also Section 4.2 "Shift-field and coercivity of the low field hysteresis loops").

If the magnetization is probed by MOKE perfectly along the steps (i.e. at $\alpha_L = 0$), it is not sensitive to the magnetization perpendicular to the steps and zero Kerr signal is detected in remanence in this case.

In a real experiment the linearly polarized laser light is usually not oriented perfectly along the steps ($\alpha_L \neq 0$). Therefore, both the magnetization component along the steps and the magnetization component perpendicular to the steps can be probed. However, if the external magnetic field is applied perfectly parallel to the steps, there is no magnetization component perpendicular to the steps and zero Kerr signal should be detected in remanence in this case.

In a real experiment, the direction of the external magnetic field (α_F) and the direction along which the magnetization is probed (i.e. the direction in the film plane defined by the plane of incoming and outgoing laser beam; α_L) are not necessarily the same (and not necessarily oriented perfectly along the steps). In this case, with no field or at low field applied along the steps ($H < H_s$), the magnetization will be oriented perpendicular to the steps. Therefore, a low field hysteresis loop corresponding to the magnetization component perpendicular to the steps can be measured. The Kerr signal can be either positive or negative depending on whether it is probed in the same or the opposite direction of the projection of the magnetization perpendicular to the steps on the laser beam direction. Thus, the low field hysteresis loop can be normal (i.e. corresponding to a positive Kerr signal at positive fields) or reversed (i.e. corresponding to a negative Kerr signal at positive fields) depending on the sample orientation.

To simplify the following discussion, we assume that $\alpha_L > \alpha_F$ (in the opposite case only the inequality signs need to be reversed). In case the laser beam orientation α_L and the field orientation α_F are both positive or both negative, the projection of the magnetization perpendicular to the steps on the laser beam direction is always oriented in the same direction in which the magnetization is probed (Fig. 1). It follows that in this case the low field hysteresis loops are always normal. The situation is different, if α_L is positive and α_F is negative. As can be seen in the schematic diagram in Fig. 2, the projection of the magnetization perpendicular to the steps on the laser beam is now always oriented oppositely to the direction in which the magnetization is

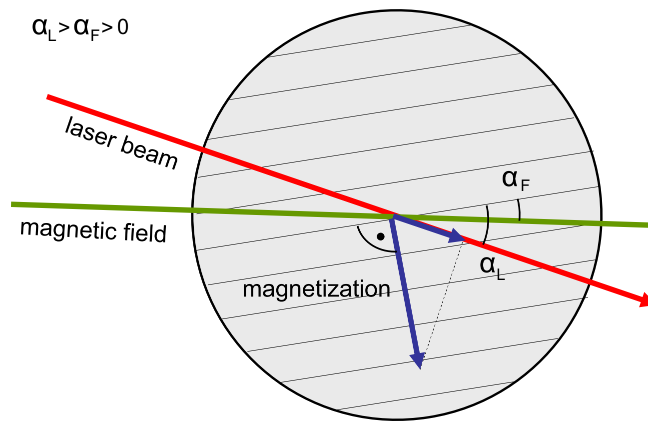

Fig. 1. Schematic diagrams showing how the laser beam and magnetic field are oriented with respect to the steps for both α_L and α_F positive (or both negative). Note that the small blue arrow which indicates the projection of the magnetization is oriented along the laser beam direction. In this case normal low field hysteresis loops are produced. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

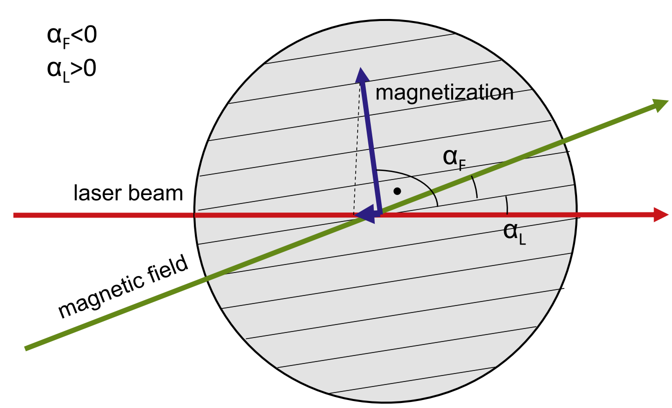

Fig. 2. Schematic diagrams showing how the laser beam and magnetic field are oriented with respect to the steps for negative α_F and positive α_L. Note that the small blue arrow indicating the projection of the magnetization is oriented opposite to the laser beam direction. In this case reversed low field hysteresis loops are produced. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

probed. Therefore, solely reversed low field hysteresis loops are measured.

2.1. In-plane anisotropy and longitudinal contributions to Kerr hysteresis loops

At first we only consider the longitudinal Kerr effect. Only the projection of the magnetization on the laser-beam direction contributes to the longitudinal Kerr signal. Therefore, the intensity of the low field contribution to the longitudinal Kerr signal ΔS_L depends on the field and the laser beam orientation with respect to the sample. From simple geometrical considerations it is expected to increase as the sine of the misalignment between the direction of the laser-beam and the step direction. Approaching $\alpha_L = \pm 90^\circ$ (i.e. probing the magnetization along the easy magnetization axis), the low field contribution reaches saturation, and rectangular hysteresis loops are measured.

By considering a small misalignment between the magnetic field and the laser-beam direction with respect to the steps in the longitudinal MOKE experiment, we can identify three different regimes of the low field contribution to the longitudinal Kerr signal ΔS_L. For positive α_F and α_L, the low field hysteresis loops are normal. ΔS_L is positive and increases from zero to saturation as $+S_L \sin(|\alpha_L|)$. Here, S_L is the saturation value of the longitudinal Kerr signal. For positive α_L and negative α_F, the low field hysteresis loops are reversed. ΔS_L is negative and decreases from zero to a finite negative value at $\alpha_F \to 0$, as $-S_L \sin(|\alpha_L|)$. For negative α_F and α_L, the low field hysteresis loops are normal and ΔS_L increases from a finite positive value to saturation as $+S_L \sin(|\alpha_L|)$. Note that the abrupt change from finite negative to finite positive ΔS_L happens because the field direction crosses the step direction, i.e. α_F changes sign.

2.2. Perpendicular magnetization component and its contribution to Kerr hysteresis loops

Perpendicular to the steps, competition between the magnetocrystalline and the shape anisotropy can tilt the magnetization out of the film plane [15–18]. Accordingly, if the magnetization is oriented perpendicular to the steps it will have a small component normal to the film plane. Whereas it will be completely in the film plane if the magnetization is oriented parallel to the steps. Since the polar Kerr effect is much stronger than the longitudinal one (roughly by one order of magnitude), even a small normal component of the magnetization can give a significant contribution to the total Kerr signal.

The question is whether the normal component of the magnetization can have an influence on the split hysteresis loops measured by probing the magnetization along the steps (i.e. along the intermediate axis). Since only the magnetization perpendicular to the steps is affected by the normal component, only the parts of the hysteresis loops that are attributed to the magnetization perpendicular to the steps will be influenced. Following the discussion above, when probing the magnetization along the steps, only the Kerr signal at low field will be influenced by the normal component of the magnetization (because only then the magnetization is oriented perpendicular to the steps). Switching of the magnetization perpendicular to the steps switches also its normal component, thus the polar Kerr effect gives an additional contribution of size ΔS_P to the low field hysteresis loops.

As long as the magnetization is oriented perpendicular to the steps the normal component of the magnetization is independent of α_F. However, as illustrated schematically in Figs. 3 and 4, the normal component of the magnetization changes polarity abruptly at $\alpha_F = 0$. Note that the actual polarity depends on the

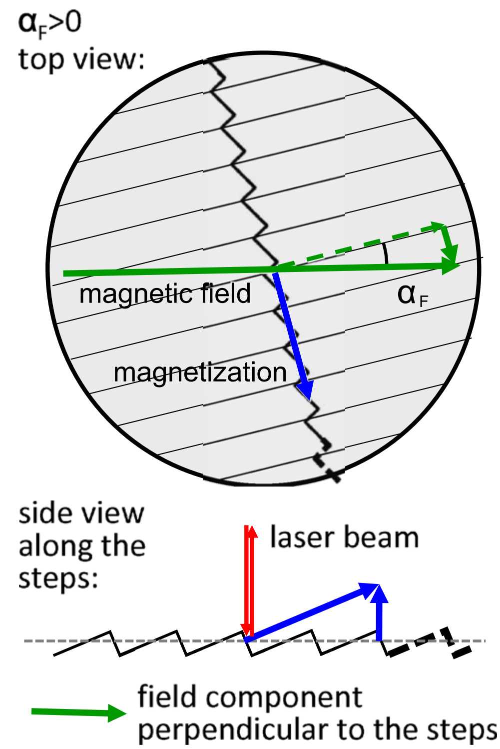

Fig. 3. Schematic diagrams of the magnetization configuration for $H < H_s$ and $\alpha_F > 0$. Note that the normal component of the magnetization, indicated by the small blue arrow in the bottom diagram, is pointing up. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

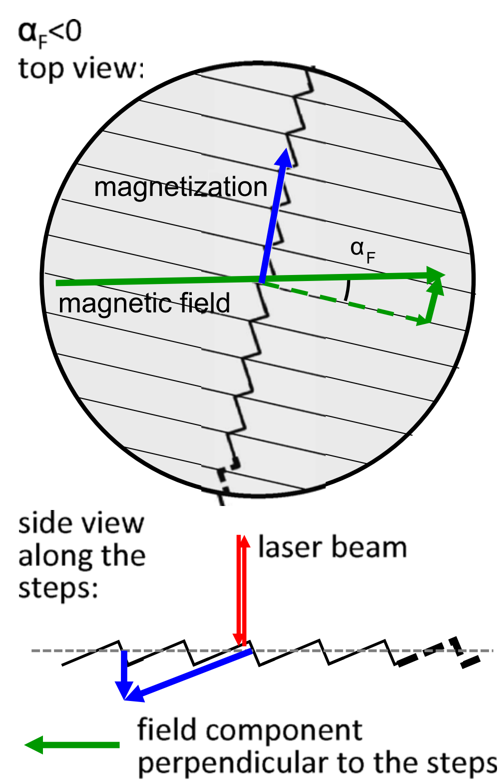

Fig. 4. Schematic diagrams of the magnetization configuration for $H < H_s$ and $\alpha_F < 0$. Note that the normal component of the magnetization, indicated by the small blue arrow in the bottom diagram, is pointing down (opposite to the situation shown in Fig. 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

step geometry and can be reversed by changing the sample orientation by 180°.

Since the incidence angle of the laser beam with respect to the surface normal is fixed by the experimental geometry, also ΔS_P will be constant apart from changing its sign at $\alpha_F = 0$. For simplicity, in the following discussion, it is assumed that ΔS_P is positive for positive α_F and negative for negative α_F.

Finally, the contributions of the longitudinal ($\Delta S_L = S_L \sin(|\alpha_L|)$) and the polar Kerr signal (ΔS_P) can be combined to $\Delta S = \Delta S_L + \Delta S_P$:

$$\Delta S = \begin{cases} -|\Delta S_P| + S_L \sin(|\alpha_L|), & \alpha_L < 0,\ \alpha_F < 0 \\ -|\Delta S_P| - S_L \sin(|\alpha_L|), & \alpha_L > 0,\ \alpha_F < 0 \\ +|\Delta S_P| + S_L \sin(|\alpha_L|), & \alpha_L > 0,\ \alpha_F > 0 \end{cases} \quad (1)$$

3. Experiment

3.1. Sample preparation

The experiments were performed in a multi-chamber UHV system with a pressure below 2×10^{-10} mbar. The Au(1,1,13) substrate was prepared by several cycles of 1 keV Ar ion sputtering and subsequent annealing at $\sim 600\,^{\circ}$C. Using scanning tunnelling microscopy (STM), nearly equidistant and regular monoatomic steps along the [1 1 0] Au direction were observed on the surface. The step direction is marked by a cut on one side of the substrate. Fe films of 15 and 58 ML thickness were grown at RT by molecular beam epitaxy. To reduce contamination during the measurements, samples were capped with a 5 ML thick Au layer.

3.2. MOKE measurements

Magnetic hysteresis loops were probed by *in situ* longitudinal (fixed incidence angle 21°) MOKE with a laser diode of wavelength 670 nm and beam diameter < 0.2 mm. In the experimental MOKE setup, the sample can be rotated in the film plane, with respect to the magnetic field and the plane of incoming and outgoing laser-beam. A continuous rotation of up to 360° with an accuracy of $\pm 0.2°$ is possible.

In the case of Au-covered Fe films grown on Au(1,1,13), independently of the Fe-film thickness, the easy magnetization axis is oriented perpendicular to the steps. Thus, split hysteresis loops are measured if the magnetization is probed (and the external magnetic field is applied) along the steps. We performed systematic studies for 15 and 58 ML of Fe on Au(1,1,13).

In order to analyze the consequences of the field component perpendicular to the steps, the sample was rotated clockwise (positive α) and counterclockwise (negative α) with respect to the orientation along which both the magnetic field and the laser-beam plane are oriented parallel to the steps. This is equivalent to the field and laser beam orientation of $\alpha_F < 0$ and $\alpha_L < 0$ for clockwise rotation of the sample and of $\alpha_F > 0$ and $\alpha_L > 0$ for counterclockwise rotation of the sample. In Fig. 5 we show three representative hysteresis loops taken for 15 ML of Fe on Au(1,1,13) at different sample orientations: (a) $\alpha > \alpha_b$, (b) $\alpha_c < \alpha < \alpha_b$ and (c) $\alpha < \alpha_c$, where α_b and α_c are chosen arbitrary since the measured loops experience qualitative changes at these angles.

(a) The hysteresis loops measured at $\alpha > \alpha_b$ show double-step behavior. In remanence a non-zero Kerr signal is observed which gives rise to an additional hysteresis loop at low magnetic field. The positive contribution to the total Kerr signal at low field decreases with decreasing α for $\alpha > \alpha_b$ and vanishes for $\alpha = \alpha_b$.

(b) The hysteresis loops measured at $\alpha_c < \alpha < \alpha_b$ show double-step behavior. The Kerr signal in remanence is still not zero and again gives rise to an additional hysteresis loop at low magnetic field. However, the shape of the low field hysteresis loops in this α range is somewhat surprising. The Kerr signal at low fields switches to positive values already at negative field and switches back to negative values only once a certain positive field is reached. This is the typical behavior of so-called reversed hysteresis loops. The contribution to the total Kerr signal associated

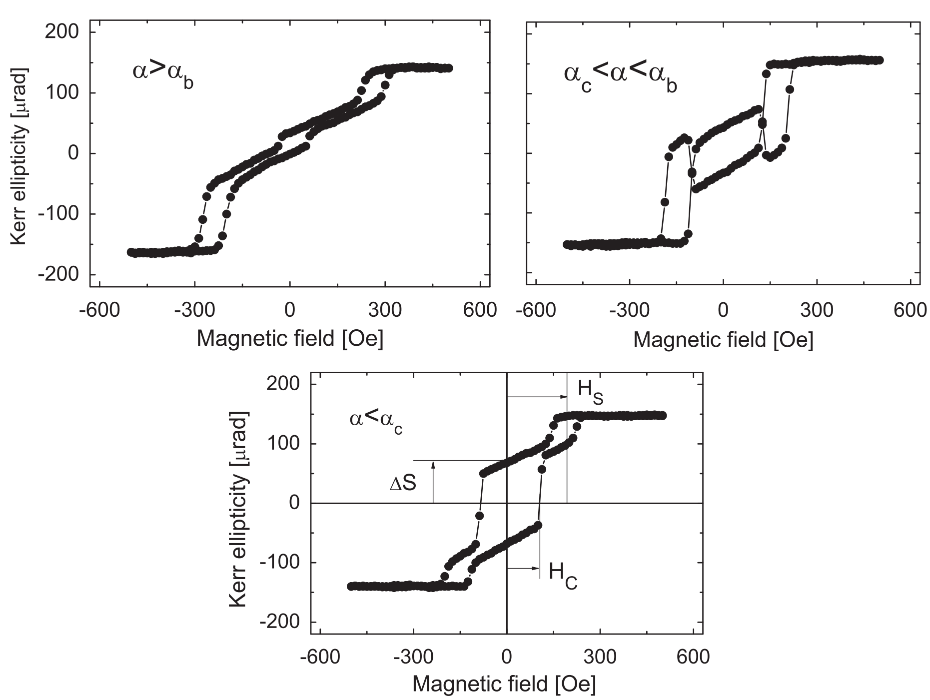

Fig. 5. Hysteresis loops measured for 15 ML of Fe grown on Au(1,1,13) at varying sample orientations α: $\alpha > \alpha_b$, $\alpha_c < \alpha < \alpha_b$ and $\alpha < \alpha_c$. Here, α_b corresponds to the sample orientation where the low field component vanishes and α_c to the orientation where the low field component abruptly changes polarity. ΔS and H_c denote remanence and coercivity of the low field hysteresis loop, respectively. H_s denotes shift field.

with the reversed hysteresis loop becomes more negative the closer α gets to α_c. The low field reversed loops result in a complex shape of the measured total Kerr hysteresis loops. The complex shape of the hysteresis loops can be explained as the superposition of the split loops with the reversed hysteresis loops (as shown in Fig. 6).

(c) The hysteresis loops measured at $\alpha < \alpha_c$ are again double-step hysteresis loops. At low field a normal (not reversed) hysteresis loop is observed, very similar to the loops measured at $\alpha > \alpha_b$. The positive contribution to the total Kerr signal at low field increases with decreasing α.

Most interesting are the loops measured at $\alpha_c \pm \Delta\alpha$, which are shown in Fig. 7. We find that it is impossible to measure hysteresis loop with zero Kerr signal in remanence at α_c. Instead, one can get two different loops for $\alpha_c \pm \Delta\alpha$, where $\Delta\alpha = 0.5^{\circ}$, with low field component of similar intensity (Fig. 7). However, for one loop the low field component is normal (for negative $\Delta\alpha$), for the second one it is reversed (for positive $\Delta\alpha$). Additionally, the coercive field of the low field hysteresis loops (i.e. the magnetic field at which the Kerr signal switches sign) increases rapidly for smaller $\Delta\alpha$.

We show only the loops measured at small α. For $\alpha = \pm 90^{\circ}$, the magnetization is probed roughly perpendicular to the steps, i.e. along the easy magnetization axis in positive ($\alpha = +90^{\circ}$) or negative ($\alpha = -90^{\circ}$) direction. The measured hysteresis loops are rectangular, but they do not show the same saturation signal (due to the polar contribution which is subtractive or additive, respectively, in agreement with previous reports [15,16]). In contrast, the measurements performed around $\alpha = 180^{\circ}$ (i.e. roughly along the intermediate magnetization axis) show exactly the same saturation signal as the ones performed around $\alpha = 0$, independent of the film thickness.

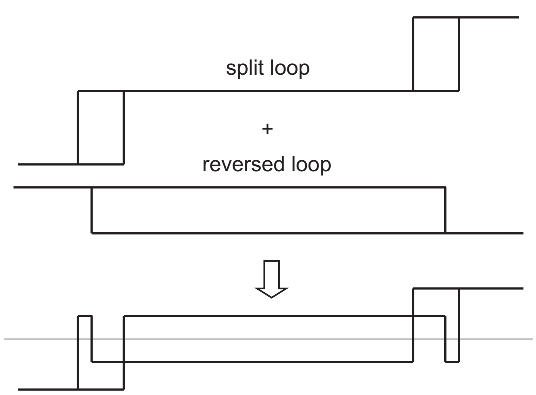

Fig. 6. Schematic of a complex Kerr hysteresis loop explained as a superposition of a split and a reversed-rectangular loop.

As shown in Fig. 8 for 58 ML of Fe on Au(1,1,13), the hysteresis loops experience changes with increasing thickness of the Fe film, as well (compare to the loops measured for 15 ML of Fe on Au(1,1,13) and shown in Fig. 5). In particular, the aforementioned complex shape of the hysteresis loops is not visible anymore for the 58 ML thick Fe films. This is because H_s decreases with increasing thickness of Fe, whereas the coercivity of the low field hysteresis loop remains more or less the same. Nevertheless, for 58 ML of Fe all the parameters of the hysteresis loops depend on the orientation α in the same way as described for 15 ML of Fe.

Obviously, the experimental observations reproduce the described model behavior of the low field component ΔS, at least qualitatively, as shown in Figs. 5, 7 and 8.

4. Moke results in view of the model

4.1. Kerr signal from the magnetization oriented perpendicular to the steps

In order to interpret the experimental data correctly, a possible contribution of the polar Kerr effect must be considered. The polar Kerr effect modifies the behavior for the longitudinal Kerr effect, in three significant ways.

If the magnetization is probed perpendicular to the steps to positive (i.e. $\alpha_L = +90^{\circ}$) and to negative (i.e. if $\alpha_L = -90^{\circ}$) direction, the polar Kerr effect is additive and subtractive, respectively. Therefore, the contribution of the polar Kerr effect $|\Delta S_P|$ can be determined quantitatively as half the difference of the saturation Kerr signal in the two directions [15]. Similarly, the saturation of the longitudinal Kerr signal S_L is given by the average of the saturation Kerr signal in the two directions.

At $\alpha_F = 0$, both the longitudinal and the polar Kerr signal at low field change abruptly in polarity (in the same sense). Hence, the characteristic orientation α_c, observed in the measured split hysteresis loops, can be identified as $\alpha_F = 0$ (i.e. as the sample orientation where the magnetic field is perfectly oriented along the steps). This orientation is chosen as a reference position, i.e. $\alpha = \alpha_c = 0$.

At $\alpha_L = 0$, the magnetization is probed perfectly along the steps. In this case no low field longitudinal Kerr signal is detected, since the magnetization perpendicular to the steps is not probed. However, a non-zero signal can be detected due to the polar contribution. For $\alpha > \alpha_c$ the loops are reversed. Only at an orientation α_b, the negative polar Kerr signal is compensated by the positive longitudinal signal. Accordingly, the characteristic orientation α_b, observed in the measured split hysteresis loops, is not equivalent to $\alpha_L = 0$ (i.e. α_b is not equivalent to the sample orientation in which the laser-beam is aligned perfectly parallel to the steps).

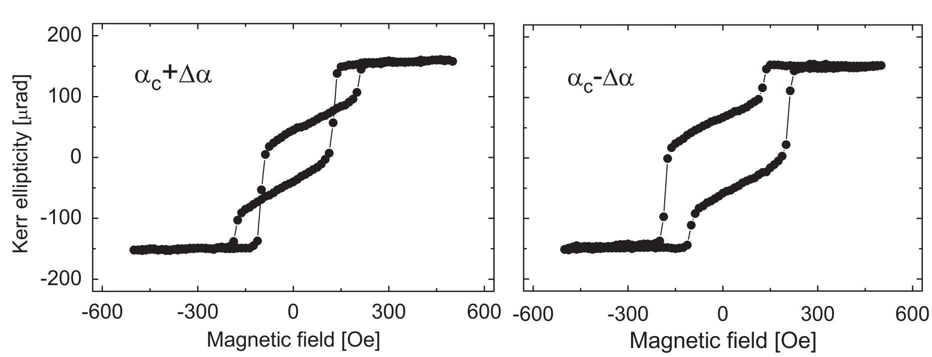

Fig. 7. Hysteresis loops measured for 15 ML of Fe grown on Au(1,1,13) at $\alpha_c \pm \Delta\alpha$, where $\Delta\alpha = 0.5^{\circ}$.

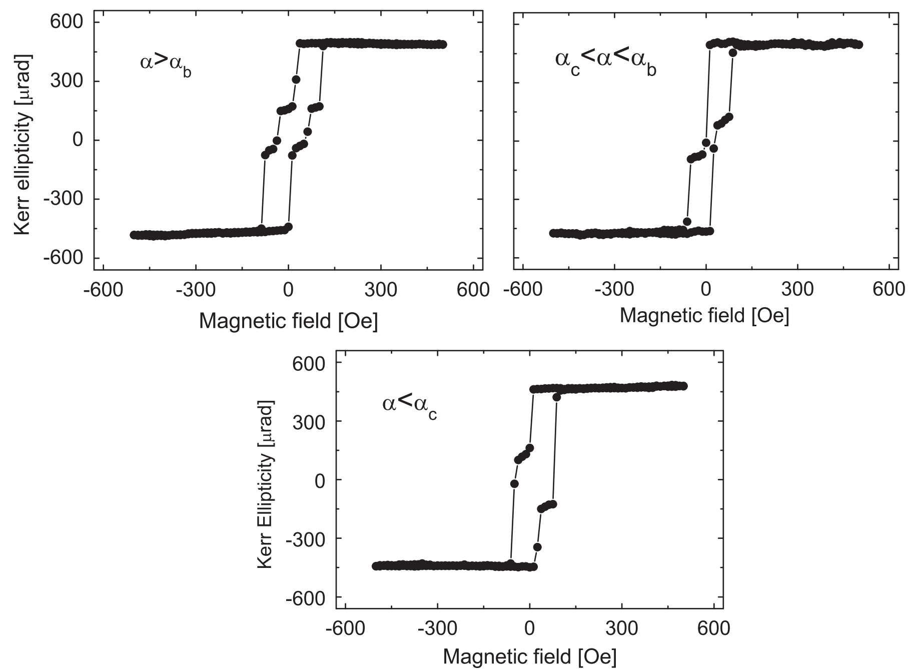

Fig. 8. Hysteresis loops measured for 58 ML of Fe grown on Au(1,1,13) at varying sample orientations α: $\alpha>\alpha_b$, $\alpha_c<\alpha<\alpha_b$ and $\alpha<\alpha_c$. The hysteresis loops were measured at the same orientations α as the ones for 15 ML of Fe shown in Fig. 5.

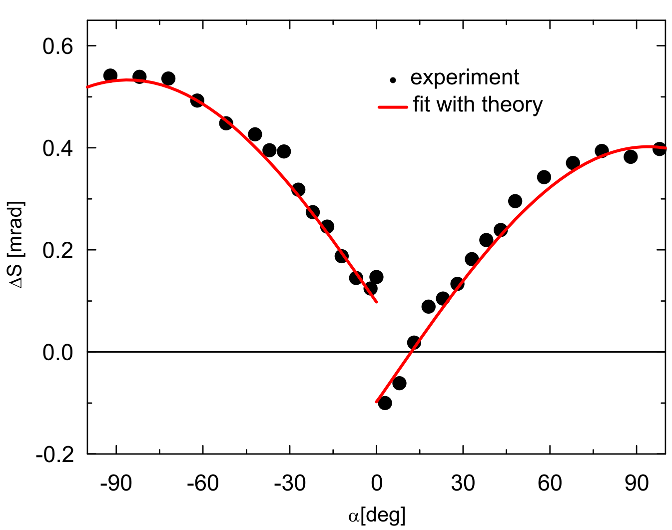

Fig. 9. Contribution to Kerr signal from the magnetization oriented perpendicular to the steps at zero field versus α for 58 ML of Fe grown on Au(1,1,13). $\alpha=0$ refers to the situation where the magnetic field is applied perfectly along the steps (i.e. for $\alpha_F=0$). Full lines represent fit with Eq. (2).

In Fig. 9, the total Kerr signal at zero field is plotted as a function of the sample orientation α. It is seen that the difference between the maximum values at $\alpha=\pm 90^\circ$ is not the same as the difference between the minimum values at $\alpha=0^\circ$. They are different because at 0° the contribution of both the polar and the longitudinal Kerr effect change in polarity, whereas at $\pm 90^\circ$ the contribution of the longitudinal Kerr effect is more or less the same and only the polar Kerr effect is of opposite polarity.

In the real experiment α is equivalent to $-\alpha_F$ (clockwise rotation of the sample results in positive α, but negative α_F). Above we defined $\alpha=0$ for the magnetic field oriented perfectly along the steps, i.e. for $\alpha_F=0$. However, since the laser-beam direction and the magnetic field direction are not necessarily the same, it is not expected that $\alpha=0$ corresponds also to $\alpha_L=0$. Thus, Eq. (1) has to be rewritten in the form:

$$\Delta S=\begin{cases} -|\Delta S_P|+S_L\sin(|\alpha-\beta|), & \alpha>\beta \\ -|\Delta S_P|-S_L\sin(|\alpha-\beta|), & \beta>\alpha>0 \\ +|\Delta S_P|+S_L\sin(|\alpha-\beta|), & \alpha<0 \end{cases} \tag{2}$$

Here β corresponds to the difference between the magnetic field and the laser-beam direction ($\alpha_L-\alpha_F=\beta$).

As described earlier, $|\Delta S_P|$ and S_L can be determined from individual hysteresis loops. This yields a value of $|\Delta S_P|=0.07$ mrad and $S_L=0.47$ mrad. Therefore, β is the only undetermined variable in the set of three equations provided above (Eq. (2)). Note that not only the three equations themselves but also their domain of definition depends on β. As a result, the three equations (Eq. (2)) can be combined to describe the expected behavior of the low field Kerr signal as a function of α, in the whole angular range. So, β can be used as a fitting parameter to fit Eq. (2) to the experimental data shown in Fig. 9. Considering the whole angular range of α, the best fit to the experimental data was found for $\beta=3^\circ$. Accordingly, the misalignment between the laser-beam direction and the magnetic field is $\alpha_L-\alpha_F=3^\circ$.

For a small misalignment of the magnetic field with respect to the laser beam direction, and with the magnetic field applied along the intermediate magnetization axis, we can generalize our results: (a) If the easy magnetization axis of the FM film is oriented perpendicular to the step direction, the larger polar Kerr effect is added to the small longitudinal Kerr effect. Therefore, split hysteresis loops with an additional large intensity Kerr loop at low fields will be measured. (b) In contrast, if the easy magnetization axis is oriented along the step direction, then only the "outer" split loops will be influenced by the polar Kerr effect. The reason is that only these parts of the hysteresis loops reflect the magnetization oriented perpendicular to the steps. In this case, the polar effect has no influence on the Kerr signal at small fields. Only the small longitudinal effect contributes to the low field hysteresis loops. Thus, much simpler split hysteresis loops with nearly no low field component are measured [4].

4.2. Shift-field and coercivity of the low field hysteresis loops

As can be seen from Figs. 5, 7 and 8, besides of the qualitative changes, the hysteresis loops display remarkable quantitative changes upon rotation with respect to $\alpha = 0$. The shift field H_s and the magnitude of the low field component to the Kerr hysteresis loop increase with increasing α. In contrast, the coercive field of the low field hysteresis loop is more or less constant and only increases rapidly close to α_c.

If the external magnetic field is not applied perfectly parallel to the steps, it affects also quantitatively the shape of the split hysteresis loops. More precisely, H_s apparently increases with increasing misalignment between the magnetic field and the step direction $|\alpha|$. The reason is that a larger total magnetic field needs to be applied with increasing misalignment, to keep the value of the magnetic field along the steps constant.

However, the measured shift field H_s (i.e. pseudo-H_s) depends on $|\alpha|$ in a more complicated manner than one would expect from simple geometrical considerations. The explanation is that the magnetic field is applied both along and perpendicular to the steps. The field component along the steps forces the magnetization to switch to the intermediate magnetization axis, whereas the component perpendicular to the steps stabilizes its orientation along the easy magnetization axis. Thus, the dependence of pseudo-H_s on α is much stronger than expected from a simple $H_s/\cos(|\alpha|)$ dependence (see Fig. 10). As can be seen in Fig. 10, the dependence of H_s on α is symmetric around $\alpha = 0$, which is another confirmation that α_c corresponds to the orientation at which the magnetic field is oriented perfectly parallel to the steps.

The fact, that the measured H_s value (i.e. pseudo-H_s) depends even stronger than expected on α, makes it clear, that an exact alignment of the magnetic field with respect to the steps is essential when H_s is evaluated quantitatively.

Similar considerations that were used to explain the dependence of pseudo-H_s on α can also be applied to understand the dependence of the coercivity H_c of the low field hysteresis loops. From simple geometrical considerations one would expect that the measured values of H_c (i.e. pseudo-H_c) depend on α as $H_c/\sin(|\alpha|)$. But as can be seen in Fig. 11 the dependence is much weaker than expected. As a result, the film magnetization can be switched with vanishingly small field perpendicular to the steps.

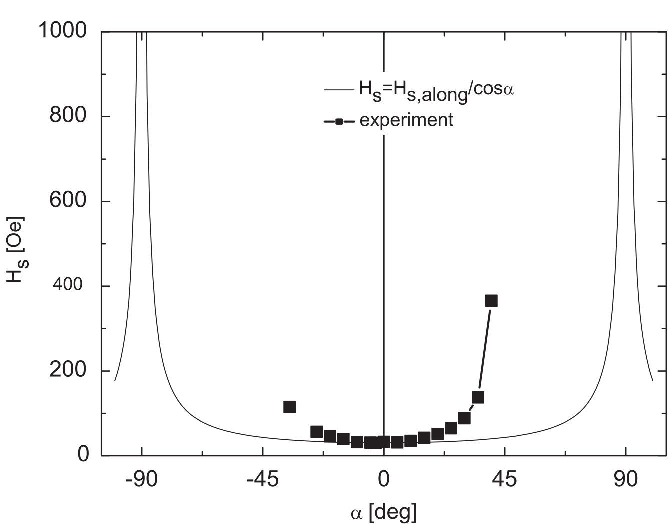

Fig. 10. Magnetic field which has to be applied to switch the magnetization of 58 ML of Fe on Au(1,1,13) from perpendicular to along the step direction (i.e. pseudo-H_s) versus α. Full line represents $H_{s,along}/\cos(|\alpha|)$. $H_{s,along}$ corresponds to the value measured for $\alpha = 0$, i.e. to the orientation where the magnetic field is applied perfectly along the steps ($\alpha_F = 0$).

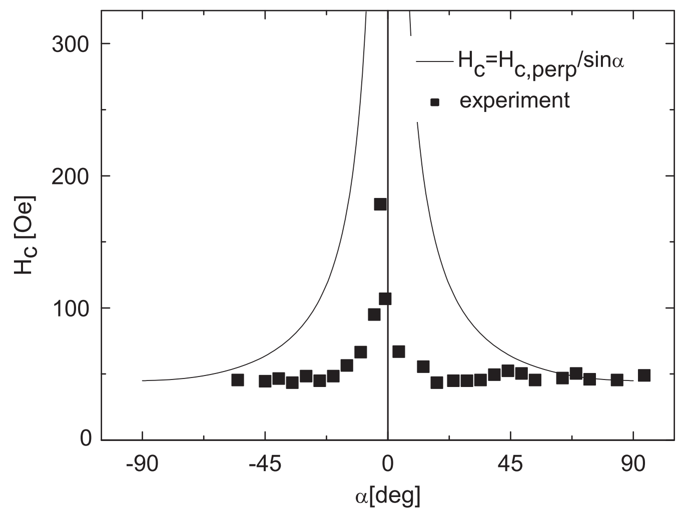

Fig. 11. Coercivity of the low field hysteresis loops (i.e. pseudo-coercivity) versus α for 58 ML of Fe on Au(1,1,13). Full line represents $H_{c,perp}/\sin|\alpha|$, where $H_{c,perp}$ refers to the real coercivity measured for the magnetic field applied perfectly perpendicular to the steps.

This can be explained by simplifying the magnetic anisotropy of the film and assuming only uniaxial anisotropy with an easy magnetization axis perpendicular to the steps and the hard magnetization axis oriented along the steps. In order to switch the magnetization perpendicular to the steps, the magnetization needs to overcome the energy barrier parallel to the steps (assuming coherent rotation). Due to the Zeeman energy, a magnetic field applied along the steps reduces this energy barrier. Therefore, the switching of the magnetization perpendicular to the steps is very easy.

The observed qualitative and quantitative changes of the split hysteresis loops are not specific to Fe films grown on Au(1,1,13) and were observed for many different film/substrate combinations. An observation, common to all investigated systems, is that split hysteresis loops with prominent low field features are only observed if the easy magnetization axis is oriented perpendicular to the steps. This can be seen in particular for Au/Fe/Ag(1,1,10) below 20 ML of Fe and for Au/Fe/Ag(1,1,6) below 10 ML of Fe (i.e. in the thickness regime where the easy axis is oriented perpendicular to the steps). In contrast, if the easy magnetization axis is oriented parallel to the steps much simpler split hysteresis loops with no low field features are measured. This is particularly evident for Au/Fe/Ag(1,1,10) above 20 ML of Fe and Au/Fe/Ag(1,1,6) above 10 ML of Fe (i.e. in the thickness regime where the easy axis is oriented parallel to the steps) [4,5].

5. Summary

In summary, we studied how magnetic hysteresis loops are influenced by the complex anisotropy present in FM films grown on stepped surfaces. We provide a model that explains why even small uncertainties in the experimental MOKE geometry can have a significant influence on the measured hysteresis loops. We find that the shift field H_s (i.e. a useful quantity to evaluate the anisotropy of FM films grown on stepped surfaces) depends on the misalignment between the magnetic field and the steps. For small misalignment angles the effect on H_s is very small, but for larger angles the dependence is much stronger than expected from geometrical arguments. model provides a simple method for an exact alignment of the magnetic field with respect to the steps and guarantees that the measured value of H_s is always the correct one. Furthermore, we show, that the split hysteresis loops are not equivalent if the easy magnetization axis is oriented parallel or perpendicular to the steps.

Acknowledgements

Fruitful discussions with F. Yildiz as well as experimental support from H. Menge, W. Greie and G. Kroder are acknowledged.

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