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

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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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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

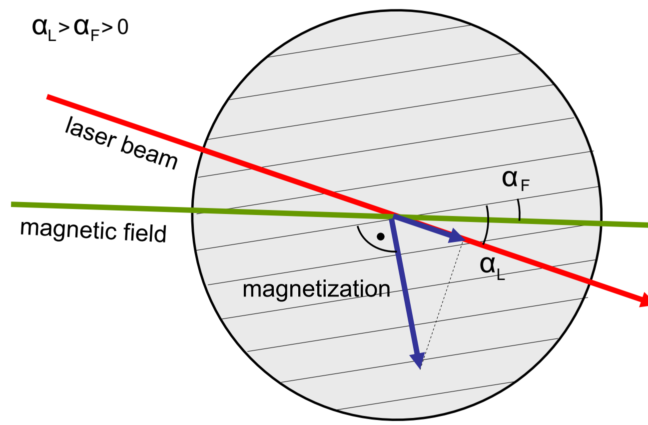

Fig. 1. Schematic diagrams showing how the laser beam and magnetic field are oriented with respect to the steps for both α_L and α_F positive (or both negative). Note that the small blue arrow which indicates the projection of the magnetization is oriented along the laser beam direction. In this case 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.)

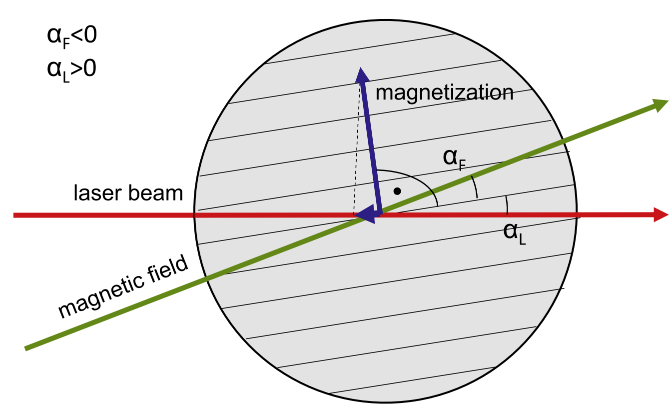

Fig. 2. Schematic diagrams showing how the laser beam and magnetic field are oriented with respect to the steps for negative α_F and positive α_L. Note that the small blue arrow indicating the projection of the magnetization is oriented opposite to the laser beam direction. In this case reversed low 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.)