A Magneto-Optical Study of Co on Step Bunched Vicinal Substrates

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Abstract- We have studied the magnetization behaviour of Co deposited on step bunched vicinal Si(111) misoriented 4° towards (11-2) using two complementary magneto-optical techniques: magnetization induced second harmonic generation (MSHG) and linear magneto-optical Kerr effect (MOKE). MSHG rotational anisotropy measurements have shown clear step induced contributions thereby allowing accurate determination of the direction of the steps. MOKE measurements exhibited a uniaxial anisotropy with the hard axis perpendicular to the step edges and an interesting bulk magnetization behaviour for intermediate angles which is shown to be due to the flipping of the magnetization of the material.

Key words: step bunching, vicinal structure, nonlinear magneto-optics, magnetization flipping, uniaxial anisotropy, thin film

1. Introduction

Recently, magnetic thin films grown on corrugated substrates have been the subject of extensive research because of the self-organization possibilities offered by these new materials for the generation and control of magnetic anisotropies^{1,2)}. To this end, several procedures have been followed which include the use of conventional vicinal surfaces²⁾ and V-groove shaped surfaces³⁻⁵⁾. A third approach is the use of the step bunching phenomenon, which can occur when a vicinal substrate is thermally pretreated in the correct way. In our case, Co deposited on a Si(111) substrate misoriented 4° towards $(11\bar{2})$ was used to achieve this kind of anisotropy.

In order to obtain a detailed insight into the magnetization behaviour of the magnetic layer, two magneto-optical techniques were used. Magnetization induced optical second harmonic generation (MSHG) is, because of its inherent sensitivity to symmetry breaking^{6,7)}, an ideal tool to study both crystallographic and magnetization induced changes at the interfaces. Combining MSHG with magneto-optical Kerr effect (MOKE) measurements which mainly probe the bulk magnetic behaviour, complementary data will yield better insight into both interface and bulk magnetic properties of the material.

The nonlinear optical polarization $P(2\omega)$, induced by an incident laser field $E(\omega)$ of a material containing a magnetization M can be described in the electric dipole approximation by⁸⁾

$$P_i(2\omega) = (\chi_{ijk}^{cr}(\pm M) \pm \chi_{ijk}^{magn}(\pm M))E_j(\omega)E_k(\omega) \quad (1)$$

where χ_{ijk}^{cr} and χ_{ijk}^{magn} denote the crystallographic and magnetization induced nonlinear susceptibility, respectively even and odd in magnetization. The interference of both contributions gives rise to the following MSHG signal $I(2\omega)$:

$$I(2\omega) \propto |\chi_{ijk}^{cr}|^2 + |\chi_{ijk}^{magn}|^2 \pm 2\chi_{ijk}^{cr}\chi_{ijk}^{magn} \cos \delta \quad (2)$$

where δ is the phase difference between both contributions.

2. Experimental Setup and Sample Preparation

For the MSHG experiments we have used a Ti:sapphire laser operating at a repetition rate of 76 MHz with a pulse width of about 140 fs and at a wavelength of 800 nm. The incoming laser light was filtered and focussed to a spot size of approximately 50 μm onto the sample with an average laser power of 30 mW. The generated second harmonic signal was detected with a cooled photomultiplier tube (PMT) and measured in the $P_{in} P_{out}$ polarization combination. The optical source for the MOKE measurements which were performed in the longitudinal configuration was a stabilized HeNe laser emitting 632.8 nm light. The reflected signal was then collected by a photodiode which was connected to a lockin amplifier. All experiments, both linear and nonlinear, have been performed at an angle of incidence of 45° .

The fabrication process of the step bunched sample starts with a Si(111) wafer misoriented 4° towards $(11\bar{2})$. In order to activate the step bunching phenomenon, this substrate is then thermally pretreated as has been described in detail by Ref. 9, reproducibly yielding a step bunched topology consisting of flat (111) terraces approximately 800 Å wide which are separated by bunches of up to 20 monoatomic steps¹⁰⁾. The overlayers are then MBE grown on the substrate, yielding the following sample structure:

Si(111)/Cu(3)/Au(30)/Cu(20)/Co(150)/Cu(20)/Au(15)

where the numbers between brackets denote the thickness in Å.

3. Results and Discussion

In Fig. 1, we present the anisotropy of the MSHG

response as a function of sample rotation around the surface normal where the magnetic field is applied in the plane of the sample and perpendicular to the plane of incidence. The sample was completely magnetically saturated in all directions.

The crystallographic contribution to the MSHG-signal originates from the 1m symmetry corresponding to the vicinal structure and the underlying 3m symmetry, which is due to the (111) surface of the Si substrate¹¹⁾. Furthermore, the magnetic contribution manifests itself in a modified intensity for opposite applied field directions. These directions cause the magnetic part of the signal to experience a phase shift relative to the crystallographic part which thereby changes the interference term in Eq. (2). Figure 1 shows a strong unidirectional behaviour in the second harmonic response which clearly shows the high sensitivity to the appearance of the steps (or step bunches): this asymmetry of the lobe structure allows very accurate determination of the direction of the steps.

The bulk magnetization behaviour of the sample has been investigated using the MOKE technique. Several hysteresis loops, as a function of sample rotation, have been measured. Typical 'hard' and 'easy' loops have been observed when the magnetic field is applied perpendicular or parallel to the step edges respectively (see Figs. 2a,b), demonstrating the uniaxial anisotropy of the step bunching phenomenon in this case.

Interesting loops have been recorded for intermediate applied field angles as can be seen in Figs. 2c,d where the magnetization seems to flip between hard and easy behaviour. To explain this 'flip'-behaviour, we made use of the Stoner-Wohlfarth (SW) model¹²⁾ which predicts a flip in magnetization at a certain field strength. The SW-energy E_{sw} , when applying a field H at an angle ϕ with respect to the hard axis can be expressed as

$$E_{sw} = K \cos^2 \theta - HM_s \cos(\theta - \phi) \quad (3)$$

Fig. 1 Rotational anisotropy of the MSHG intensity in the transversal geometry for opposing magnetic field directions. The numbers denote the angle of the applied field relative to the hard direction, i.e. perpendicular to the step edges. The inset shows the angle relative to the

steps.

Fig. 2 Longitudinal MOKE hysteresis loops with the applied field at 0° (a), 90° (b), 50° (c) and 11° (d) relative to the hard direction. The insets show the direction of the applied

magnetic field relative to the steps.

in which K is the anisotropy constant, θ the angle between the magnetization and the hard axis and M_s the saturation magnetization of the material.

It can be shown that for an increasing value of H applied between the hard and easy direction, one minimum of E_{SW} as a function of θ at a certain field strength H_f called the flip field, disappears abruptly, forcing the magnetization to flip to a different angle. With further increase of the field, the magnetization will start to align itself again with the applied field and finally reach saturation. This is schematically shown in Fig. 3.

Because of the fact that, while performing MOKE-measurements, we are actually probing the parallel component of the magnetization relative to the applied field, a 'dip' in the MOKE-signal could be interpreted as:

$$\cos \psi_i - \cos \psi_f > 0 \quad (4)$$

where ψ_i and ψ_f denote the angles between the magnetization and the applied field before and after the flip respectively. A negative value for Eq. (4) indicates a normal flip in the MOKE hysteresis loop as shown in Figs. 2b,c.

In Fig. 4, we present the flip magnitude normalized to its value along the easy direction as a function of the applied field angle. The data agrees very well with the theoretical dependence, including a 'dip' region spreading over 14° starting at the hard direction.

In Fig. 5 we report the flip field normalized to its value along the hard direction as a function of the angle of applied field. The data shows a very nonuniform behaviour in comparison to the SW model which exhibits a uniform mode of flip. The thickness corresponding to the change of regime depends on the interplay between the anisotropy, which is frustrated in the uniform mode, and the exchange which is frustrated in the nonuniform mode. This nonuniform behaviour has previously been observed for other (thinner) Co thicknesses in identical structures¹⁰⁾, where the behaviour became more SW-like with increasing thickness. This was interpreted as being dominated by the large decrease in the anisotropy field for the thickness range studied. However, in our thicker case, the behaviour has reverted to a nonuniform mode, resembling the thinnest sample in Ref. 10. We observe a less pronounced decrease in anisotropy and as the sample is probably thicker than the exchange length it can be qualitatively understood that the system has evolved towards a mode of reversal which is frustrating the exchange.

4. Conclusion

In conclusion, we studied Co deposited on step bunched vicinal Si(111) using two complementary magneto-optical techniques. MSHG rotational anisotropy was observed which was explained by taking three contributions into account. A clear 1m symmetry was

Fig. 3: SW energy as a function of the angle of magnetization with an applied field at 13° relative to the hard direction, for increasing magnetic field strengths. At the flip field strength ($\approx 0.635 H_A$, where $H_A = 2K/M_s$) the minimum vanishes and the magnetization flips to a different angle.

Fig. 4 Flip magnitude normalized to its value along the easy direction as a function of the angle of applied field relative to the hard direction. The solid line represents the theoretical dependence according to the SW model.

Fig. 5 Flip field dependence normalized to its value along the hard direction on the angle of applied field (solid dots). The solid line represents the dependence according to the SW model. The values are normalized to the flip field in the hard direction.

found to be due to the vicinal structure of the sample allowing accurate determination of the step edges, whereas an underlying 3m symmetry appeared to be originating from the Si(111) interface. A magnetic contribution manifested itself by a modified intensity response for opposite field directions. MOKE measurements revealed clear 'hard' and 'easy' behaviour and interesting loops for intermediate angles of applied field exhibiting 'flip'-behaviour. This behaviour was explained with help of the SW-model which showed the disappearance of the energy minimum at a certain field strength called the flip field. Measurements of the flip field as a function of the angle of applied field were consistent with literature, whereas the magnitude of the flip was in excellent agreement with theory.

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