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Morphology and magnetism of thin Co films on textured Au surfaces

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Abstract

Magnetization and domain structure of thin cobalt wedges on textured Au substrates were studied by scanning electron microscopy with polarization analysis (SEMPA). In the thickness regime with perpendicular magnetization, as-grown films contain small domains with diameter between 0.3 and 1.5 μm. The small size is connected to the morphology of the film, resulting from the textured nature of the Au substrate. Applying a magnetic field gives a distinct dependence of measured polarization on film thickness, most likely caused by variations in coercivity. Results are compared with those obtained for similar films on single crystal Au substrates, in view of the relation between magnetic properties and morphology.

Keywords: Magnetization; Thin films; Scanning electron microscopy – SEMPA; Morphology; Domain structure

1. Introduction

Concerning magnetic materials, the preparation of multilayer structures has revealed fascinating phenomena, such as perpendicular magnetic anisotropy, giant magnetoresistance and oscillatory exchange coupling. Although the existence of these effects can be attributed to the layered nature and the presence of interfaces, they are generally in a more subtle manner influenced by film structure, morphology and composition. This equally applies to other properties like coercivity and dynamical behavior.

Recently, the interplay between film morphology and magnetism of thin Co films on Au(111) was studied using SEMPA [1]. For as-grown Co films on single crystal Au(111) substrates, domains between 2 and 5 μm have been observed in the thickness range with perpendicular magnetization [1–3]. This in contrast to the prediction of a single domain state based on calculations [4]. In Ref. [1] it was demonstrated that the domain structure can be drastically modified by changes in the film morphology, resulting from annealing (film smoothening and Au diffusion on top of the Co). Hence, it was concluded that domain sizes in the as-grown film are controlled by film morphology, which was not accounted for in the calculation.

To further investigate the relation between film morphology and domain structure, we have studied similar films prepared on a substrate with different morphology, i.e. textured Au(111) layers grown on floatglass substrates. Structural and magnetic properties of Au/Co/Au layers on floatglass have already been extensively studied (see for example Refs. [5–7]), however, mainly with ex situ techniques and films capped with a second Au layer. For such films it was already shown that film imperfections play a decisive role in hysteresis [8] and dynamic behavior of domains [9,10]. In this paper we will present in situ measurements on the Co/Au/floatglass system with SEMPA, discuss the relation with substrate texture and make a comparison with results for single crystal substrates. A detailed study of Co growth on textured Au substrates by scanning tunneling microscopy (STM), will be presented elsewhere [11].

2. Experiment

Au layers of 180 Å thickness were evaporated onto floatglass substrates at a rate of 1 Å per minute in a pressure below 2×10^{-9} mbar. They were subsequently annealed at 150°C and exposed to air during transport to another ultrahigh vacuum system in which the SEMPA measurements were performed. In this system, with a base pressure of 8×10^{-11} mbar, the Au substrates were cleaned by mild Ar-ion sputtering at 500 eV for 5 min, followed by annealing at 150°C. A carbon contamination of about 10% was detected with Auger electron spectroscopy. A line-shaped Co wedge was then deposited, having a width of

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300 μm and a slope of 0.8 monolayer (ML) per 100 μm. It covers the thickness range from 0.9 to 20 ML. The evaporation rate was 0.3 ML/min. and the pressure 5×10^{-10} mbar during evaporation. Details about the SEMPA system can be found in Ref. [12]. All data was obtained at room temperature.

3. Results

A typical example of the magnetic domain structure of Co on textured Au substrates is presented in Fig. 1. The 10×10 μm^2 image shows the perpendicular component of the spin polarization, at a section of the wedge with 3.0 to 3.1 ML Co thickness. The in-plane component vanishes. Small oppositely magnetized domains with irregular shape and diameter between 0.3 and 1.5 μm are observed. Basically the same results were obtained at 2.1 and 4.2 ML, except that around 4.2 ML the first in-plane domains appear. Thus, also in this case small domains are found, instead of a single domain state. Moreover, the domains are almost a factor of 10 smaller than those reported for as-grown Co on Au single crystals [1,3].

As a first step towards understanding the microscopic origin of the small domain size, we have examined the texture of the Au substrate layers by atomic force microscopy (AFM). A representative example of the surface topography of a Au layer is presented in Fig. 2. In the scan area of 3×3 μm^2 we observe regions of Au crystallites with atomically flat terraces separated by monatomic steps. In these regions the average crystallite diameter is about 80 nm, which is an order of magnitude smaller than the size of magnetic domains (Fig. 1). Some very rough areas

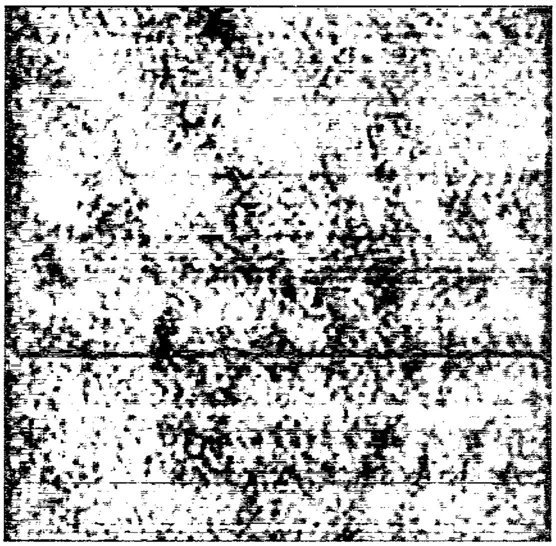

Fig. 1. SEMPA image (10×10 μm^2) of an as-grown Co film with 3.0 to 3.1 ML thickness. Only the perpendicular component is shown, the in-plane signal vanishes.

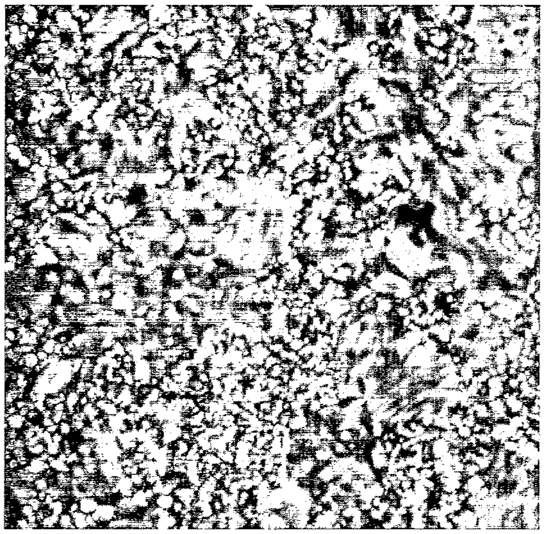

Fig. 2. AFM image of a textured Au layer on floatglass. Scan size is 3×3 μm^2.

also appear in Fig. 2, with crystallites as small as 10 nm, and trenches as deep as 2 nm between them. The relatively flat and rough regions, respectively, have a size on the order of a micron, and each take up about half of the total surface area.

To further investigate the magnetic properties, a magnetic field of 90 Oe was applied perpendicular to the sample surface. SEMPA images were then taken with an increased scan range of 500×500 μm^2, covering the complete perpendicular magnetization region and part of the in-plane magnetization region. Both the perpendicular and one of the in-plane polarization components are displayed in Fig. 3. The start of the wedge at 0.9 ML is indicated near the lower left corner, while the Co thickness increases towards the upper right corner. Five regions can be distinguished.

In region a below 1.9 ML no polarization signal was detected. Higher resolution images in this area also showed no sign of small domains, such as in Fig. 1. In regions b, c and d we find a clear non-zero perpendicular polarization, while the in-plane polarization is negligible. Above 4.3 ML (region e) the polarization is mainly in plane, although some perpendicular signal persists (upper right corner). More quantitative data is given in Fig. 4, showing the perpendicular polarization as a function of film thickness between 1.3 and 5.5 ML. The signal sets in at 1.9 ML, reaches an initial maximum (in the absolute value) at 2.1 ML (5%), and decreases again in region c to about 2%. Region d, however, shows a larger polarization again (11%), while above the spin reorientation transition at 4.3 ML the perpendicular signal is non-zero [13]. Note that due to the limited number of data points, the polarization in Figs. 3 and 4 represents an average over an area of 2

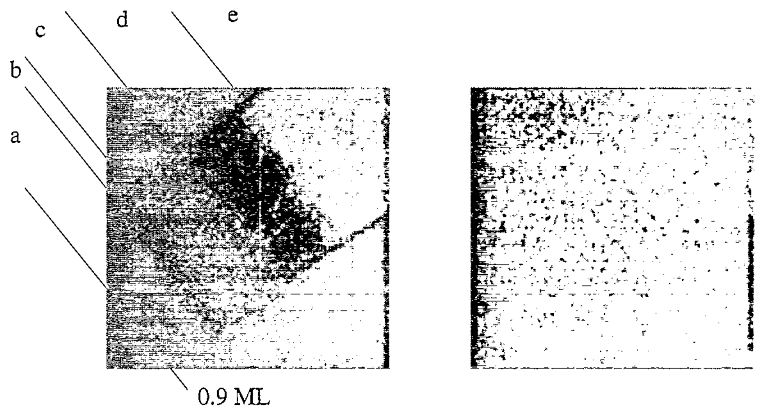

Fig. 3. 500×500 μm^2 image of a Co wedge after magnetizing with 90 Oe perpendicular to the film plane. Left image shows the perpendicular spin component, the right image one of the in-plane components. Regions a to e are indicated, see text for further explanations.

μm. No polarization is then found in case of small domains.

4. Discussion

Using textured Au substrates, we have found domains between 0.3 and 1.5 μm, i.e. almost an order of magnitude smaller than those in Co on single crystal substrates. The difference is obviously induced by the different substrate roughness. Crystallite boundaries with high step density in the relatively flat areas, as well as very rough areas with small crystallites are present. Both are expected to influence Co growth and provide a significant amount of nucleation and pinning sites for domain walls. There is however a striking similarity in the sizes of flat and rough areas on the one hand, and magnetic domain size on the other hand. This suggests a relation between domain formation and spatial roughness variations. In this respect the

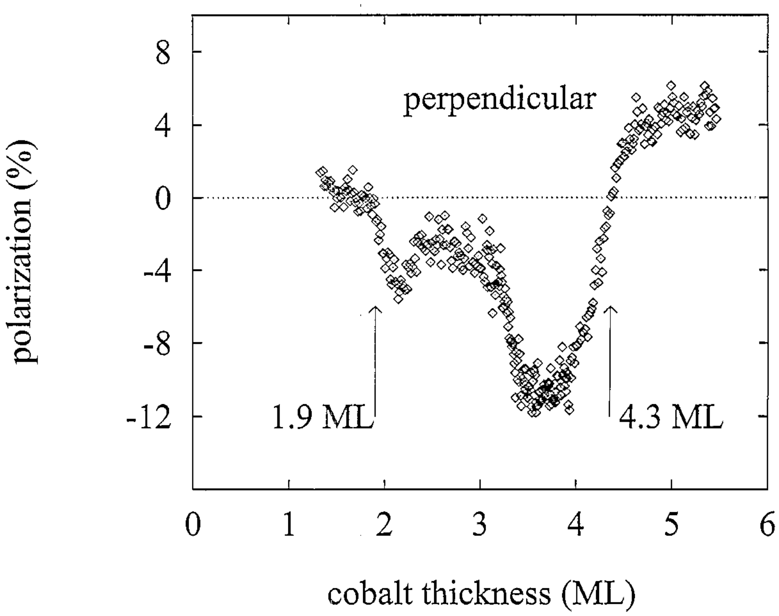

Fig. 4. Perpendicular spin polarization versus film thickness. The critical thickness, where the magnetization switches from perpendicular to in-plane, is indicated at 4.3 ML.

boundaries between the different regions seem to play an important role. A detailed study of Co film growth might clarify the exact mechanism.

The absence of polarization below 1.9 ML is in agreement with preliminary STM data, showing the development of the Co into a continuous film around 2 ML. This allows ferromagnetic coupling over larger regions of the film. The remarkable polarization variation between 1.9 and 4.3 ML might be explained by a variation of coercivity with Co thickness. Whenever the coercive field is too large, a single domain state cannot be reached with the maximum available field (90 Oe). Small reverse domains will then persist, and the polarization averages to a lower value. This interpretation suggests that the polarization reduction above 2.1 ML is caused by an increase of coercivity with film thickness, as was for example also found for Co on Cu(001) [14]. Similarly, it suggests a decrease of the coercivity towards the reorientation transition at 4.3 ML. This was also reported for Au/Co/Au/floatglass [8], and explained by a diminishing importance of interfacial roughness for trapping domain walls, as the film becomes thicker.

For comparison, as-grown films on single crystal Au(111) substrates can be forced into a single domain state with a 90 Oe field for the whole perpendicular magnetization range [15]. The measured polarization is also more than a factor 2 higher than our maximum value of 11%. The lowered value can be explained by local variations in substrate roughness, as found by AFM (Fig. 2), leading to spatial variations in coercivity. Small reverse domains will then persist in regions with highest coercivity. However, other explanations such as a lower saturation magnetization or the presence of nonmagnetic parts are possible too. The problem might be solved by direct real-space correlation of micromagnetic structure and morphology, which remains a challenge for spin-polarized microscopies at this length scale.

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