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MBE growth of Fe(211)/Au(110) multilayers on MgO(110) substrates

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A 0.9 nm-Fe(211)/3.1 nm-Au(110) superlattice has been grown and measured by SQUID magnetometry. The magnetization has been found in the plane and the easy direction is [01$\bar{1}$] due to tension strain along the [$\bar{1}$11] axis. A weak antiferromagnetic coupling across the Au layers (0.01 erg/cm^2) has been deduced.

1. Introduction

Thin layers, sandwiches or superlattices involving Fe have been extensively studied for both the (100) [1–5] and the (110) [6,7] growth axis. However, to our knowledge, the only experiment on the (211) direction has been carried out by Ueda et al. [8], with single layers grown on copper by electrodeposition. They reported unusual magnetization effects, because of the in-plane strain induced by the specific orientation of iron on the substrate.

In this paper, we show that Fe(211)/Au(110) superlattices may be grown. The magnetic measurements are discussed and related to the structural analysis of the sample.

2. Growth and structural characterization

A high quality Au(110) buffer has been obtained on a MgO(110) substrate via a thin Fe(211) seed layer (2 nm). The details of the growth of the buffer may be found elsewhere [9,10]. The structure of the bcc Fe layer deposited on Au(110) at room temperature looks like that of Fe on MgO(110): two kinds of equivalent domains have been characterized with the following epitaxial relationships:

$$\begin{aligned} &\mathrm{Fe}(211)[\bar{1}11]\|\mathrm{Au}(110)[1\bar{1}0], \\ &\mathrm{Fe}(211)[1\bar{1}\bar{1}]\|\mathrm{Au}(110)[1\bar{1}0] \end{aligned} \quad (1)$$

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A superlattice has been grown with 30 periods (0.9 nm Fe and 3.1 nm Au). Reflection High Energy Electron Diffraction (RHEED) has been performed during the growth. The half order streaks of the Au(1 × 2) reconstruction reappear when about eight atomic Au layers have been deposited on the iron layer. The intensities of the Bragg spots of iron and gold are periodic with a nearly constant amplitude during the whole superlattice growth (see fig. 1). Therefore, the structure of the stacking may be considered as homogeneous.

X-ray reflectivity measurements have shown that the roughness of the interfaces is of the order of 0.6 nm. X-ray diffraction (XRD) measurements have revealed three satellites lines near the buffer Au(220) peak. A weak Fe(211) peak appears with a full width at half maximum (FWHM) of about 0.7° leading to a coherence length of about 17 nm. The mosaic width of the

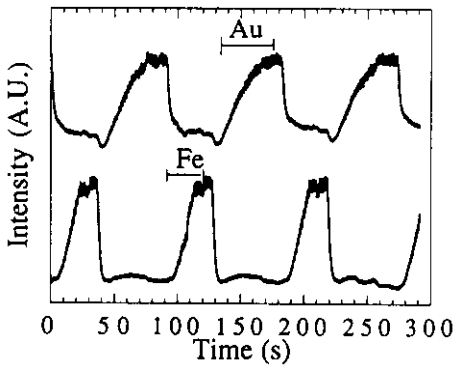

Fig. 1. RHEED intensity of the Bragg spots of Fe and Au during the growth of the superlattice. Only three periods are represented.

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Fe(211) peak is 0.6° and that of the Au satellites is 0.5°. The in-plane coherency length is thus of the same order of magnitude as the perpendicular one. In spite of the roughness of the interfaces, the coherency seems to be spread over more than the size of one bilayer.

3. Magnetic measurements

The hysteresis loops of the sample have been measured by SQUID magnetometry at 300 K with the external field applied in three directions: [211] perpendicular to the surface and [01$\bar{1}$] and [$\bar{1}$11] parallel to the surface of the sample. The saturation magnetization has been estimated to be 1881 emu/cm^3. This value is very close to that of the bulk iron (1714 emu/cm^3). The slight difference may be explained by a little increase of the magnetic moment of the iron. We rather believe this difference to be related to the uncertainty in the Fe volume. Figure 2 shows the normalized hysteresis loops in the range of the high fields. Clearly the magnetization is hard to saturate when the applied field is normal to the surface. The required field is about 10 kOe, which is high but less than that predicted from pure shape anisotropy: $H_{sat} = 4\pi M_s = 21$ kOe. This reduction of the perpendicular anisotropy seems too strong to be attributed to a magnetocrystalline anisotropy effect. More likely, it may be explained by a large interface roughness which reduces the dipolar energy anisotropy [11]. The saturation field may be written:

$$H_{sat} = 4\pi M_s\left(1 - \frac{3\sigma}{4d}(1-f)\right), \tag{2}$$

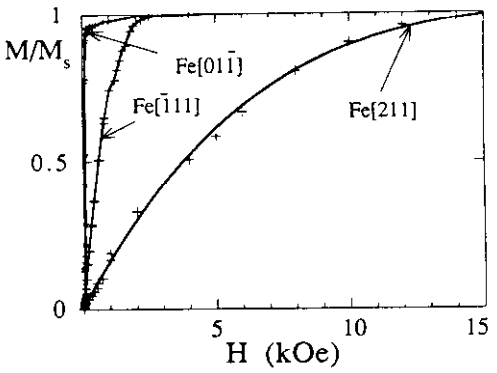

Fig. 2. Magnetization curves with the external field applied in the three principal directions.

where d is the layer thickness, σ is the mean roughness and f is a decreasing function of the ratio of σ and the correlation length of the roughness. The reduction of the saturation field from 21 kOe to about 10 kOe leads to a large roughness effect: $\sigma(1-f) \approx 0.5$ nm. This seems to be in agreement with the value found by X-rays reflectivity measurements.

In spite of the reduction of the shape anisotropy, the magnetization remains in the plane of the sample or at least nearby. As no ⟨100⟩ easy magnetocrystalline direction lies in the plane, we will try in the following to determine what is the easiest direction in the plane. Taking into account only the magnetocrystalline anisotropy, the anisotropy energy may be expressed in terms of the in-plane angle θ between the magnetization and the [$\bar{1}$11] direction:

$$E_c = K_1(\cos^4\theta/3 + \sin^4\theta/4). \tag{3}$$

This expression leads to an easy direction of magnetization for about $\theta = 49°$. Moreover, similar hysteresis loops would be expected in the [01$\bar{1}$] or [$\bar{1}$11] in-plane directions. On the contrary, fig. 2 clearly shows that the easy direction is [01$\bar{1}$]. Then an in-plane uniaxial anisotropy has to be added to the magnetocrystalline anisotropy:

$$E_u = K_u\cos^2\theta \tag{4}$$

The constants K_1 and K_u may be estimated by fitting the hysteresis loop when the field H is applied in the hard direction [$\bar{1}$11]. In that case, indeed, the applied field is related to the normalized magnetization by the expression:

$$H = \frac{7K_1}{3M_s}\left(\frac{M}{M_s}\right)^3 + \frac{2K_u - K_1}{M_s}\frac{M}{M_s}. \tag{5}$$

Hence, we obtain: $K_1 = 6.5 \times 10^5$ erg/cm^3 and $K_u = 13 \times 10^5$ erg/cm^3. The value of K_1 almost agrees with that of the bulk crystal ($K_1 = 4.8 \times 10^5$ erg/cm^3) and it is within the range found by Ueda et al. [8] for Fe(211)/Cu. The value of K_u is larger than that of Ueda et al. but of the same order of magnitude. However, the differences of thickness and substrate make the comparison only qualitative. The origin of this large uniaxial

anisotropy is probably due to strain as it was pointed out by Ueda et al. In our case, iron and gold have a good lattice relationship in the Fe[01$\bar{1}$]||Au[001] direction. But in the Fe[$\bar{1}$11]||Au[1$\bar{1}$0] direction, a misfit of about 15% leads to a tensile strain η for iron, which is between 0 (total relaxation) and 15% (perfect coherency). Assuming that the strain is only in the [$\bar{1}$11] direction, the contribution of the magnetoelastic energy to the magnetic anisotropy may be written as:

$$E_e = -3c_{44}\lambda_{111}\eta \cos^2\theta. \quad (6)$$

By using $c_{44} = 11.6 \times 10^{11}$ dyn/cm^2 [12] and $\lambda_{111} = -21.2 \times 10^{-6}$ [13] the uniaxial anisotropy constant K_u may be written:

$$K_u = 74 \times 10^6 \eta \text{ erg/cm}^3. \quad (7)$$

Then an iron strain of only 2% is needed to take into account the estimated uniaxial anisotropy constant. But a more severe strain is expected from RHEED measurements. The discrepancy arises maybe because we have ignored the perpendicular strain and/or the higher order terms in the development of the magnetoelastic anisotropy. Anyhow, this single model gives the good sign and the good order of magnitude to explain the in-plane uniaxial anisotropy.

Fig. 3 represents the magnetization in the easy direction [01$\bar{1}$]. The iron seed layer contribution has been substracted; we measured it on a calibration sample onto which no multilayer had been deposited. The hysteresis loop exhibits a weak magnetization plateau between $H_s = -55$ and 55 Oe. This effect is characteristic of antiferromagnetic (AF) coupling between ferromagnetic layers. The coupling strength per unit area is estimated by: $J = M_s H_s d = 0.01$ erg/cm^2. This

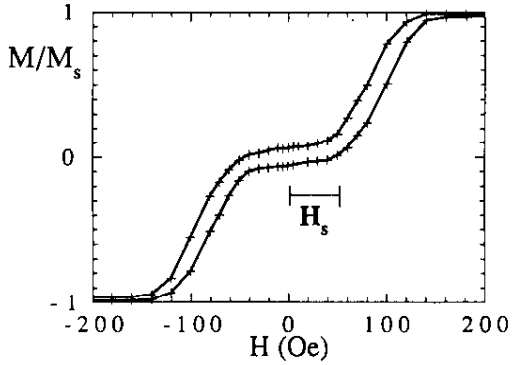

Fig. 3. Hysteresis loop with the field in the [01$\bar{1}$] direction. The contribution of the Fe seed layer has been subtracted.

small AF coupling may be compared to the results of Celinski et al. [3]. They found a weak maximum AF coupling of the same order of magnitude in Fe(100)/Au(100)/Fe(100) sandwiches with 13 ML = 2.6 nm gold layers.

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