1. Introduction

Metallic multilayers (MLs) composed of alternating sublayers of ferromagnetic (FM) and non-magnetic metals has attracted great interest over the past years because of the successful application of these materials as ultrasensitive hard disc reading heads and magnetic sensors [1, 2]. Since the discovery of antiferromagnetic (AFM) interlayer coupling in Fe/Cr/Fe trilayers [3], magnetic exchange coupling of ferromagnetic sublayers across a nonmagnetic spacer has been the subject of numerous experimental and theoretical studies. It has been shown that oscillatory exchange coupling is a general phenomenon for most transition-metal and noble-metal elements [8] or using hydrogen [9, 10]. In the later case it could be tuned not only by electronic structure but also thickness of the spacer. Furthermore, as a model system V(001)/Fe(001) multilayers were used very recently to study finite size effect [11]. In this paper we report on strong and weak exchange coupling of the Fe sublayers across vanadium spacer in V(110)/Fe(110) multilayers.

2. Experimental details

The V/Fe multilayers were prepared at room temperature using UHV (5 × 10⁻¹⁰ mbar) magnetron sputtering [12]. The number of repetition of the base period was equal to 25. A capping layer of 5 nm Pd was used to allow a fast uptake and release of hydrogen at a temperature of less than 370 K and to avoid oxidation of the MLs. As a substrate we have used Si(100) wafers with an oxidised surface to prevent a silicide formation [13]. Therefore we have applied a special heat treatment in UHV before deposition in order to obtain an epitaxial SiO₂ surface layer [13, 14]. The Fe-layers with d₉₀ = 0.6 nm were deposited using a DC source. For preparation of the V-layers (0 < d₉₀ < 5 nm) a RF source was used. In the case of V/Fe MLs a 1.6 nm-V buffer layer was first deposited to enhance the (110) growth. In Fig. 1 we show schematic description of the construction of the multilayered samples. The chemical composition and the cleanness of all layers was checked in situ, immediately after deposition, transferring the samples to an UHV (4 × 10⁻¹¹ mbar) analysis chamber equipped with X-ray photoelectron spectroscopy (XPS), Auger electron spectroscopy (AES) and ion gun etching system. Details of the XPS measurements can be found in Ref. [15].

The morphology and roughness of the Pd capping layers were studied ex situ by atomic force microscopy (AFM). The structure of the V/Fe MLs was examined ex situ by standard θ–2θ X-ray diffraction with Cu Kα radiation. The modulation wavelength was determined from the spacing between satellite peaks in the high and low-angle X-ray diffraction patterns.
The thicknesses of individual Fe and V sublayers were also determined using X-ray fluorescence analysis (XRF) and X-ray reflectivity (XRR).

The magnetic characterisation of the samples was carried out using a vibrating sample magnetometer (VSM) at room temperature. The remanence $(M_r)$ and saturation magnetisation $(M_s)$, and saturation fields $(H_s)$ were determined from the in-plane hysteresis loop measurements in magnetic fields up to 2 T.

3. Results and discussion

The composition modulation of the V/Fe MLs was confirmed in the high- and low-angle X-ray diffraction measurements by intense satellite peaks. The wavelengths of modulation calculated from these peaks were in agreement with those values determined from XRF. In the high-angle XRD patterns we have observed central Bragg peak located between positions expected for reflections of bcc-Fe(110) and bcc-V(110) and at least two satellites for the MLs with the thinner sublayers. The fitted roughness from the XRD data was about 0.3-0.4 nm, which is in agreement with AFM measurements [16]. Results on structural characterisation will be published in more details in a separate paper [17].

In the XPS experiment we have also studied the Fe layer growth on a 1.6 nm-V underlayer. The freshly deposited 1.5 nm-V-$d_s$-Fe bilayer was in situ transferred from the preparation chamber to the analysis chamber, where the XPS Fe 2p$_{3/2}$ and V 2p$_{3/2}$ core level spectra were immediately measured in vacuum of $8 \times 10^{-11}$ mbar. Then the bilayer was transferred back to the preparation chamber and the deposition process of the Fe overlayer was continued. The above procedure (overlayer deposition and XPS core level measurements) was repeated until the Fe 2p$_{3/2}$ and V 2p$_{3/2}$ integral intensities were saturated. Practically no trace of oxygen (or any other contaminants) adsorption or surface oxide formation was detected during the transfer operation or XPS measurements ($\approx 10$ min). From the exponential variation of the XPS Fe 2p and V 2p integral intensities with increasing overlayer Fe (V) thickness up to 5 nm we conclude that the Fe and V sublayers grow homogeneously in the planar mode [16, 17]. We have previously observed very similar growth mode for Fe/Ti [18] and Fe/Zr [19] bilayers.

In Fig. 2 we show the room temperature hysteresis loops measured for the 1.15 mm-V/0.6 nm-Fe and 1.6 nm-V/0.6 nm-Fe MLs. The Fe/V multilayer with $d_V = 1.6$ nm shows zero remanence value and saturation field greater than 1 T at room temperature. The above result confirms the AFM coupling across vanadium spacer. The shape of the hysteresis loop revealed also a biquadratic component of the interlayer coupling.
suppresses the AFM coupling peaks between Fe layers at \(d_V \approx 0.7\) and 1 nm. However, because the direct exchange coupling decays more quickly than the indirect RKKY coupling between Fe layers, we have observed at least three other AFM coupling features (see Fig. 3a) for \(d_V > 1\) nm. The observed difference of the interlayer exchange coupling presented in Fig. 3a and Ref. [20, 21] could be explained not only by different growth conditions and crystallographic orientations but also specific polarization of vanadium spacer near V–Fe interfaces. Let us note that after hydrogenation process [16] we have observed small decrease of the total magnetic moment of our samples. Such behaviour reveals rather positive polarization of the first atomic V interface layer and negative polarization of the second atomic interface layer as reported in Ref. [22]. Furthermore, the observed different ranges and period of the AFM coupling strength across V could also depend on modification of the Fermi surface for ultrathin V(110) films observed experimentally in Ref. [23].

In conclusions, we have observed short period oscillation of the AFM interlayer exchange coupling of the Fe layers across V spacer in V/Fe(110) multilayers due to indirect RKKY-type coupling. The direct exchange coupling of V atoms near V–Fe interfaces probably suppresses the AFM coupling peaks between Fe layers for \(d_V \leq 1\) nm.

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References

Fig. 3. Saturation field (a) and remanence (b) as a function of V layer thickness \(d_V\) for the V/Fe MLs.

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