

Strong and Weak Interlayer Exchange Coupling in V/Fe Multilayers

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The d_V -V/0.6 nm-Fe multilayers with constant thickness sublayers were prepared onto naturally oxidised Si(100) substrate using UHV (5×10^{-10} mbar) DC/RF magnetron sputtering. Results showed that the saturation field of the V/Fe multilayers oscillate with antiferromagnetic interlayer exchange coupling peaks near the V spacer thickness of about 1.3, 1.6, 2.05 nm. Furthermore, all the samples with vanadium layer thickness near local maxima of the antiferromagnetic coupling show zero remanence. The short period of the antiferromagnetic peak oscillations is due to indirect Ruderman–Kittel–Kasuya–Yosida (RKKY)-type coupling of the Fe layers across vanadium spacer. The absence of the antiferromagnetic peaks in the very strongly coupled region (below $d_V \approx 1$ nm) could be explained by direct ferromagnetic exchange coupling of the Fe layers due to magnetic polarization of V atoms near V–Fe interface.

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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 spacer [4]. The experimentally determined oscillation periods are in agreement with theory based on the interplay between the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction and the discrete spacer thickness [5]. The same behaviour of the oscillatory exchange coupling was achieved in another picture: quantum wells in the spacer produced by the different spin states of the electrons in the ferromagnets [6]. In addition to the oscillating bilinear coupling as a function of the spacer thickness, the transition zones between ferro- and antiferromagnetic type were characterised by 90° -type coupling [7].

In general, the magnetic properties of MLs can be tailored by varying the composition, thickness and microstructure of the magnetic and non-magnetic sublayers. The strength and sign of the interlayer exchange coupling could be tuned by alloying the spacer with nonmagnetic elements [8] or using hydrogen [9, 10]. In the later case it could be changed 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 $d_{Fe} = 0.6$ nm were deposited using a DC source. For preparation of the V-layers ($0 < d_V < 5$ 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 $\theta - 2\theta$ X-ray diffraction with Cu K_α radiation. The modulation wavelength was determined from the spacing between satellite peaks in the high and low-angle X-ray diffraction patterns.

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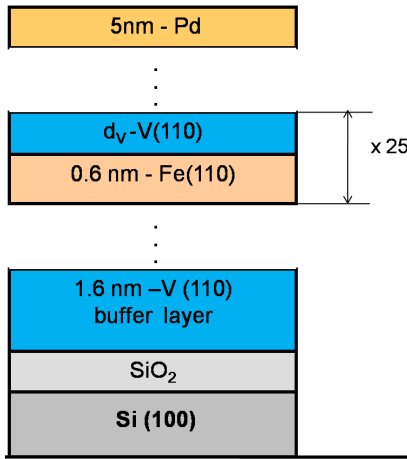


Fig. 1. Schematic presentation of the construction of the prepared V/Fe multilayers.

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_o -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 8×10^{-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 contaminations) adsorption or surface oxide formation was detected during the transfer operation or XPS measurements (≈ 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 nm-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.

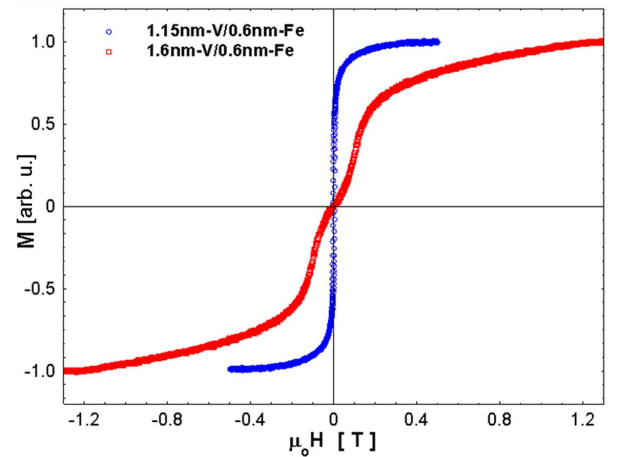


Fig. 2. In plane hysteresis loops of 0.6 nm-Fe/1.15 nm-V and 0.6 nm-Fe/1.6 nm-V MLs.

Results on the saturation field and remanence studies as a function of the V interlayer thickness are shown in Fig. 3a and b, respectively. As can be observed, the H_s and remanence show near $d_V \approx 1.3, 1.6, 2.05$ nm local maximum and zero values, respectively. The above behaviour indicates an oscillation of the AFM exchange coupling between Fe sublayers across V spacer with period of about 0.3–0.4 nm. The oscillation period of the AFM coupling determined previously for V/Fe(001) superlattices was about 0.8 [20] and 1 [21] nm for iron layer thickness of about 0.45 and 1 nm, respectively. The position of our 3rd AFM peak in Fig. 3a is very similar to that observed earlier for V/Fe superlattices with $d_{Fe} \approx 0.45$ nm and (001) orientation [20]. On the other hand, for V/Fe superlattices with the same orientation and thicker Fe layer ($d_{Fe} \approx 1$ nm) the first AFM peak was observed near $d_V \approx 2.2$ nm [21].

The absence of the AFM peaks in the very strongly coupled region (below $d_V \approx 1$ nm) could be explained by direct ferromagnetic exchange coupling of the Fe layers due to magnetic polarization of V atoms near V-Fe and Fe-V interfaces [21, 22]. The induced V moments were characterized by a “transient” ferromagnetic state, with strong V–V direct exchange coupling with d - d character [21]. This direct exchange coupling probably

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 polarisation 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].

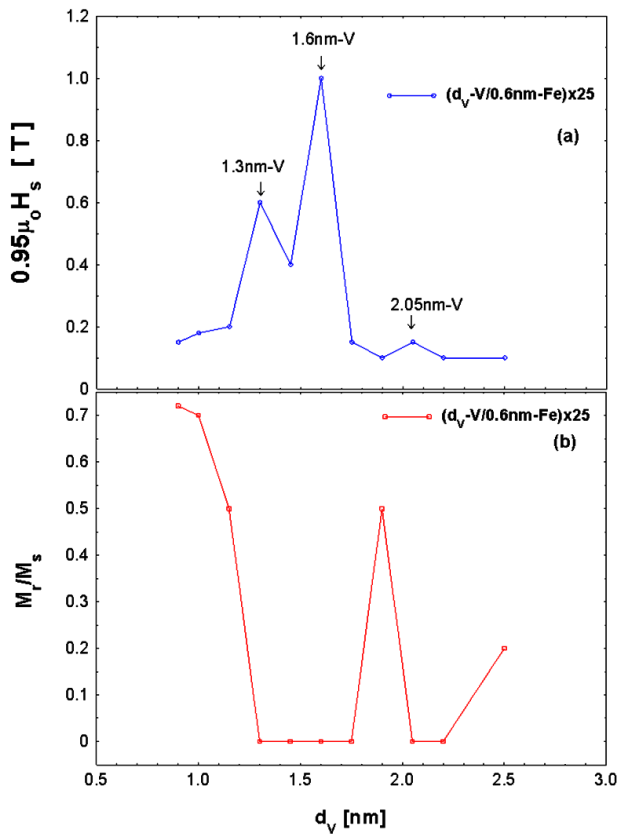


Fig. 3. Saturation field (a) and remanence (b) as a function of V layer thickness d_V for the V/Fe MLs.

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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