Journal of Magnetism and Magnetic Materials 422 (2017) 362–366

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Induced magnetism at the interfaces of a Fe/V superlattice investigated by resonant magnetic x-ray scattering

Martin Magnuson

Department of Physics, IFM, Thin Film Physics Division, Linköping University, SE-58183 Linköping, Sweden

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form
15 July 2016
Accepted 1 September 2016
Available online 3 September 2016

Keywords:
Superlattice
Reflectivity
Induced magnetic moments
Synchrotron radiation

ABSTRACT

The induced magnetic moments in the V 3*d* electronic states of interface atomic layers in a Fe(6ML)/V (7ML) superlattice was investigated by x-ray resonant magnetic scattering. The first V atomic layer next to Fe was found to be strongly antiferromagnetically polarized relatively to Fe and the magnetic moments of the next few atomic layers in the interior V region decay exponentially with increasing distance from the interface, while the magnetic moments of the Fe atomic layers largely remain bulk-like. The induced V moments decay more rapidly as observed by x-ray magnetic scattering than in standard x-ray magnetic circular dichroism. The theoretical description of the induced magnetic atomic layer profile in V was found to strongly rely on the interface roughness within the superlattice period. These results provide new insight into interface magnetism by taking advantage of the enhanced depth sensitivity to the magnetic profile over a certain resonant energy bandwidth in the vicinity of the Bragg angles.

1. Introduction

In the quest for improved applications in magnetism, the fundamental mechanism for the magnetic coupling in superlattices for magnetic data storage and magnetic anisotropy has been in focus for a long time [1]. Superlattices are also of technological interest as mirrors in the soft x-ray region using alternating layers of high and low density elements to significantly enhance the reflectivity in a narrow range around the Bragg angles [2]. Metallic ferromagnetic (FM) layers such as Fe, that are separated by a nonmagnetic spacer layer such as V exhibit an oscillating interlayer exchange coupling (IEC) that is either FM or antiferromagnetic (AFM) depending on the spacer layer thickness [3,4]. As a model system, Fe/V superlattices have been used to study the IEC [5], the induced magnetic moments in V [6], and the giant magnetoresistance (GMR) effect [7]. Fe/V superlattices have also been shown to be possible hydrogen storage media whereby the hydrogen modify the electronic structure of the nonmagnetic (NM) spacer layer as well as the magnetic interlayer coupling [8]. When a Fe/V multilayer is grown in the (110) plane on a MgO(001) single crystal, the IEC between successive Fe layers oscillatory couple FM and AFM [9]. However, magnetometry measurements indicated a periodic oscillating coupling as a function of V interlayer thickness with Fe AFM coupled at 22 Å, 32 Å and 42 Å [10] but no AFM coupling peak was observed at 12 Å (7 ML) V layer thickness.

Previous studies of the size and extent of the V polarization in Fe/V superlattices have mainly been studied by x-ray magnetic circular dichroism (XMCD) at the 2*p* absorption edges in total electron yield (TEY) mode [11]. For Fe/V superlattices, it was found that the induced average V magnetic moments increase with thinner V or Fe layers [12]. Although vanadium is non-magnetic in bulk form, it obtains a weakly induced magnetic moment in a Fe/V superlattice due to hybridization with Fe at the interfaces that is normally aligned antiparallel to those of Fe [13]. More detailed XMCD studies came to the conclusion that the atomic layer resolved induced magnetic moments of V decay monotonically and slowly with distance from the Fe interface so that even the fourth and fifth atomic layers from the interface possessed a significant magnetic moment [14,15]. These observations are at variance with calculated results [16], where the induced magnetic moment of V is most significant at the first layer in contact with Fe while the magnetic moments in the interior atomic layers are negligible. However, the limited probe depth in the TEY mode of about 15 Å in XMCD [17] is not useful when capping layers are utilized to prevent surface oxidation of superlattices.

For the investigation of local magnetic properties in deep buried layers, bulk-sensitive x-ray magnetic scattering (XRMS) is better suited [18]. While the wavelengths in the soft x-ray regime are usually too long for Bragg diffraction of single crystals, they are very suitable for larger periodic structures such as multilayers with lattice spacing of a few monolayers. With the use of circularly or elliptically polarized synchrotron radiation in the excitation, a dichroic XRMS spectrum is the difference in scattered intensity obtained with opposite relative orientations of the photon spin

E-mail address: Martin.Magnuson@ifm.liu.se

http://dx.doi.org/10.1016/j.jmmm.2016.09.009
0304-8853/

(helicity) of the incident x-rays and the applied magnetization direction of the sample [19–23]. In previous XRMS investigations on thin superlattices, it was found that the technique is sensitive to changes in the optical constants [24] along the surface normal that depend on the local magnetic properties and therefore it can be used to distinguish between different shapes of magnetization depth profiles [25,26].

In this paper, we investigate the magnetic coupling and quantify the induced V magnetic moments at the interfaces of a (Fe 6 ML)/(V 7 ML) superlattice by taking advantage of the large probe depth and element selectivity of the XRMS technique at resonant conditions. By utilizing the enhanced magnetic sensitivity by the rapidly changing refractive index at energies around the 2*p* absorption resonances in combination with the constructive interference scattering at the interfaces in the vicinity of the Bragg angles, it is shown that it is possible to use a relatively limited data set to distinguish between different magnetization profiles of the weakly induced moments at the interface and in the interior regions of the V spacer layers of a Fe/V superlattice.

2. Experimental details

The XRMS measurements were performed using the reflectometer at the soft x-ray metrology bending magnet beamline 6.3.2 at the Advanced Light Source (ALS) in Berkeley, USA [27,28]. The out-of-plane elliptically polarized radiation was extracted by using a four-jaw aperture in the beamline. The monochromator was set to a resolving power of 2000 and a flux of 10^{10} photons per second on the sample at the Fe and V L_3-edges. The sample was magnetized along the (100) easy axis, parallel to its surface and in the scattering plane (longitudinal mode), by means of a permanent magnet (0.1 T), situated behind the sample holder, mounted on a stepper motor, used to reverse the field direction at each photon energy. The energy scans were performed at three different θ-angles at both the Fe and V 2*p* thresholds (680–730 eV and 500–545 eV, respectively) with a 0.2 eV step size. The incoming flux was monitored and used to normalize the spectra. The incident photons were 60% circularly polarized and the sample was mounted in the reflectometer end station with the axis of rotation parallel to the orbit plane.

The single-crystal Fe/V thin film superlattice was epitaxially grown in ultrahigh vacuum by dual-target magnetron sputtering deposition of metallic Fe and V layers on a polished MgO(001) fcc single crystal substrate at 300 °C [29]. The superlattice was grown in the (110) plane and is thus rotated 45° with respect to the (100) direction of the substrate. A biaxial compressive strain on V and a tensile strain on Fe results in a body centered tetragonal (bct) structure due to the lattice strain and mismatch at the interface of 5.1% between bulk Fe and bulk V. The alternating depositions of the Fe and V layers were repeated to form a total of 40 bilayer periods and capped with a 40 Å Pd film to prevent oxidation.

Analysis of the structural parameters was made by x-ray diffraction (XRD) before fitting the spectroscopic XRMS part. The structural quality of the sample was checked and the layer thicknesses determined by using conventional θ–2θ XRD measurements with Cu K_α radiation ($\lambda = 1.54$ Å) for low angles (1.5–15° in 2θ) and high angles (50–80° in 2θ) around the Fe/V (002) Bragg peak. Fig. 1 shows reflectivity (top panel) and x-ray diffraction data (bottom panel) of the Fe/V superlattice. The low-angle data (top panel), show well-defined Bragg peaks denoted 1–3, arising from the chemical modulation, surrounded by small Kiessig fringes that appear from interference between the surface and bottom of the whole film. The appearance of the third Bragg peak in the reflectivity data indicates that the interface roughness is small. By fitting the angular positions of the Kiessig fringes to a linearization

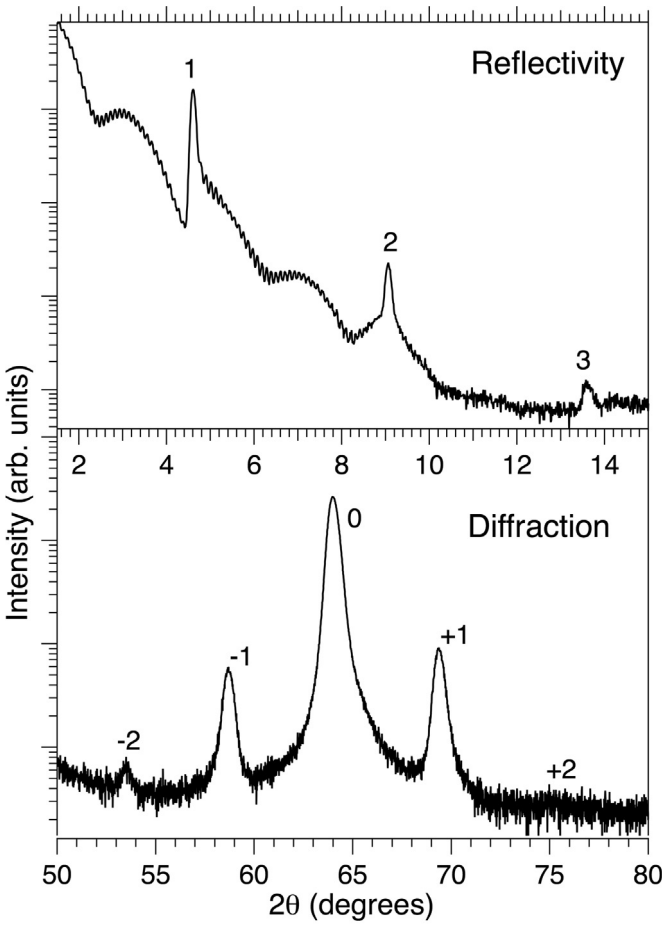

Fig. 1. X-ray reflectivity and diffraction of the Fe(6ML)/V(7ML) superlattice measured with conventional θ-2θ Cu K_α radiation ($\lambda = 1.54$ Å) x-ray source. (a) Low-angle x-ray reflectivity data with the main x-ray diffraction (XRD) peaks indicated. (b) High-angle XRD where the main superlattice 002 peak indicated by "0" is surrounded by satellites denoted ± 1 and ± 2.

of Bragg's law, the total film thickness was determined to be 830 ± 2 Å and the number of periods to 40.

From the high-angle diffraction measurements (bottom panel), the periodicity Λ of the multilayer was determined from the angular positions of the intense (002) Bragg peak and the satellites according to Braggs law: $\Lambda = n \times \lambda/\{2(\sin\theta_n - \sin\theta_0)\}$, where "0" is the main Bragg peak and $n = \pm 1$ and ± 2 are the satellites on both sides. Table 1 lists the structural parameters of the individual layers with error bars obtained by a successive refinement procedure to reproduce the Bragg peaks of the XRD data using the computer program SUPREX [30]. The periodicity $\Lambda = t_1 + t_2$ was determined to be 19.7 ± 0.1 Å and the individual thicknesses of Fe 7.4 ± 0.1 Å (6ML) and V 12.3 ± 0.1 Å (7ML). From the XRD fitting, the Pd capping layer was determined to be 40 ± 1 Å thick.

Table 1
Structural parameters for the (Fe 6 ML)/(V 7 ML) superlattice. The total film thickness is 830 ± 2 Å and $t = t_{Fe}/(t_{Fe} + t_V) = 0.38$.

Period 19.7 ± 0.1[Å]	Fe	V	Pd	MgO
Thickness [Å]	7.4 ± 0.1	12.3 ± 0.1	40.0 ± 1.0	∞
Roughness [Å]	1 ± 0.5	1.5 ± 0.5	1.5 ± 0.5	2 ± 0.5
Density [10^3kg/m^3]	7.9	6.1	12.0	1.44
Atomic weight	55.8	50.9	106.4	20.15