Fe/V and Fe/Co (001) superlattices: growth, anisotropy, magnetisation and magnetoresistance

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Some physical properties of bcc Fe/V and Fe/Co (001) superlattices are reviewed. The dependence of the magnetic anisotropy on the in-plane strain introduced by the lattice mismatch between Fe and V is measured and compared to a theoretical derivation. The dependence of the magnetic anisotropy (and saturation magnetisation) on the layer thickness ratio Fe/Co is measured and a value for the anisotropy of bcc Co is derived from extrapolation. The interlayer exchange coupling of Fe/V superlattices is studied as a function of the layer thickness V (constant Fe thickness) and layer thickness of Fe (constant V thickness). A region of antiferromagnetic coupling and GMR is found for V thicknesses 12-14 monolayers. However, surprisingly, a ‘cutoff’ of the antiferromagnetic coupling and GMR is found when the iron layer thickness exceeds about 10 monolayers.

I. INTRODUCTION

The magnetic properties of the transition elements are critically dependent on fine details of the electronic structure of the d-electrons. Thus, any changes of the symmetry or interatomic distances as well as restrictions in dimensionality of the system could introduce striking changes of the magnetic properties. Artificial, but controlled, changes of symmetry, interatomic distances and dimensionality are readily introduced in Fe and Co when they are grown on single crystalline substrates in the form of thin films or superlattices. Such layered structures allow systematic studies of the dependence of major magnetic properties on e.g. controlled magnitudes of the induced strains. In this article we review results from some recent studies of the magnetic properties of (001) bcc iron and cobalt.

II. GROWTH

Bcc Fe/V (001) and Fe/Co (001) superlattices were grown on MgO (001) substrates by UHV dc sputtering. The lattice constants of the involved materials are: Fe (2.87 Å), V (3.03 Å), MgO (4.21 Å) and bcc Co (2.82 Å) (bcc Co does not exist naturally, but the lattice parameter is estimated from extrapolation from values for Fe(Co) alloys). The lattice mismatch between Fe and V is small enough to allow epitaxial growth and still large enough to introduce relevant strain in the individual Fe layers. The in-plane strain introduced in the samples due to the lattice mismatch causes a symmetry breaking and the true crystallographic structure of the samples becomes body centred tetragonal (bct). The superlattices grow with an [100] direction of MgO, yielding a lattice mismatch of -4% for iron and 2% for V. The samples were grown under optimal conditions and the crystallographic properties of the samples were measured by different X-ray techniques certifying the crystallographic quality as well as giving measures of the lattice parameters of the superlattices and the individual layer thicknesses.

III. MAGNETIC AND TRANSPORT PROPERTIES

The magnetic and transport properties of the samples were investigated using a QD MPMS5 SQUID magnetometer and an Oxford Maglab 2000 system.

A. Fe/V - magnetic anisotropy energy

The in-plane magnetic anisotropy energy (MAE) of different Fe/V samples was derived from measurements of magnetisation curves along the in-plane [100] and [110] directions of the films. No uniaxial contribution to the MAE was found in any of the samples, which also certifies a good bct crystallographic structure of the superlattices. The quite significant lattice mismatch between Fe and V allows studies of the anisotropy as a function of in-plane lattice strain of Fe. Samples of constant iron layer thickness (15 monolayers (ML)), but varying V thickness (1-12 ML) are studied, the in-plane lattice parameter of the samples increases with increasing thickness of the V layers. Experimental average in and out of plane lattice parameters were derived from X-ray diffraction and were complemented by theoretical calculations of the common in-plane and individual out of plane lattice parameters.
using tabulated elastic constants for Fe and V. The measured and calculated average lattice parameters agreed fairly well and the theoretically derived individual in and out of plane lattice parameters could then safely be used for theoretical calculations of the magnetic properties.

The saturation magnetisation of the superlattices was found to be reduced in comparison with bulk iron, amounting to 1.9 $\mu_B$ compared to 2.2 $\mu_B$ for bulk iron. The reduced magnitude can partly be explained by an induced weak antiferromagnetically aligned magnetic moment in the vanadium interface layers. Fig. 1 shows the measured magnetic anisotropy as a function of lattice strain at 10K. The corresponding theoretically calculated values for strained bulk iron are also included in the figure. These values have been derived using the magnetoelastic constants of iron and the known anisotropy for unstrained bulk iron. The calculated strain dependence of the MAE is remarkably similar to that experimentally observed, but there is a significant downward shift of the measured MAE compared to that of bulk iron, which can be assigned to a surface contribution favouring [110] as the easy direction at the Fe/V interfaces.

When discussing anisotropy of Fe/V superlattices it should be noted that superlattices grown to form (110) planes do show a totally dominating uniaxial in-plane anisotropy of a magnitude that is comparable to the out of plane anisotropy and the influence of the bcc symmetry breaking. Fig. 1 shows the reduced magnitude can partly be explained by an in-plane anisotropy and the influence of the bcc symmetry breaking. One interesting future study of the current (001) Fe/V system would thus be to investigate the anisotropy of these superlattices by e.g. ferromagnetic resonance (FMR) to get the full picture of both the in-plane and the out of plane anisotropy and the influence of the bcc to bct symmetry breaking.

B. Fe/V - GMR

The Fe/V (001) system has also been studied as to the magnetoresistance and interlayer coupling strength as a function of the V or the Fe layer thickness. In the investigated range of V thicknesses (2-16 ML), the interlayer coupling shows one antiferromagnetic maximum centred at V $\approx$ 13 ML. Fig. 2 shows the dependence of the magnetoresistance for two sample series with vanadium thicknesses of 11 and 13 ML and varying Fe thickness. The 11 ML V samples show only an anisotropic magnetoresistance (AMR) of increasing magnitude with increasing iron layer thickness. However, the 13 ML V samples show GMR for thin to intermediately thick Fe layers, but for thicker Fe layers the GMR (and the antiferromagnetic (AF) inter-layer coupling) disappears. The GMR effect is superposed by a weak AMR of similar magnitude as observed in the non-AF coupled superlattices. The most surprising feature is the appearance of a cut-off of the GMR occurring for iron thicknesses larger than about 10 ML, leaving only an AMR effect in the samples. This apparent cut-off of the AF-coupling finds no support in current theory and the physical origin of it is thus not yet understood. However, the fact that the current samples consist of 30 bilayer repetitions causes some magnitude mismatch between the magnetisation of the AF coupled Fe layers. This yields a net magnetic moment that could be large enough to interfere with the AF coupling and destroy the regular AF magnetic structure throughout the sample that is necessary to give the GMR effect and a measurable AF-coupling strength.

C. Fe/Co - magnetisation and magnetic anisotropy

Cobalt does not naturally crystallise in the bcc structure, it is however possible to grow bcc Co as a superlattice intervened with Fe. These bcc Fe/Co superlattices show intriguing magnetic properties. The magnetisation curves for an iron rich and a Co rich superlattice with bilayer thicknesses 6/2 and 2/6 are shown in Fig. 3. There is a change of sign of the anisotropy energy as the system becomes richer on cobalt. In Fig. 4 the magnetic anisotropy energy (MAE) between the [100] and [110] directions is plotted vs. Co content in Fe/Co samples of bilayer thicknesses (x/y) as indicated in the figure. There is a closely linear dependence of the anisotropy energy on concentration. An extrapolation to pure Co gives a value of the MAE that has opposite sign and about twice the magnitude of the MAE of bulk iron. However, one should keep in mind that there can be a significant contribution from the interface regions (cf the results above on the Fe/V system) that may move the MAE curve downward as compared to what would be observed for pure bulk iron and pure but artificial bulk bcc cobalt.

The saturation magnetisation of the different samples are shown in Fig. 5. The values are given in $\mu_B$/atom. There are several features to note in this figure. The most striking is that the magnitude of the magnetisation is significantly larger than that of corresponding Fe/Co alloys, i.e. there is an interface enhancement of the magnetic moments. The current data gives a possibility to phenomenologically assign a specific value of the magnetic moments of Fe and Co in the atomic layers at the interface and deeper into the magnetic layers. Doing this, one finds a significant enhancement of the iron moments at the interfaces, and also up to some 4 layers away from the interface. To account for the observed behaviour one has also to introduce an oscillating nature of the magnetisation in the layers having the largest magnitude at the interface, a value close to the bulk value one atomic layer away and then again significantly enhanced values in the following two atomic layers to finally settle at the bulk iron value deep into a thick Fe-layer. It was also found necessary to introduce a significantly enhanced Co moment at the interface. The enhanced value of the magnetisation in a superlattice as compared to the
corresponding bulk alloy does ask for further experimental and theoretical studies, since current theory does not predict such a big change and basically no enhancement of the Co moment at the interfaces.

IV. CONCLUSIONS

The magnetism of the transition metals (e.g. Fe and Co) depends critically on the symmetry and volume of the lattice. These parameters are readily varied in theoretical calculations and the magnetism of the elements can be mapped out for any artificial crystallographic structure. One possibility to check these predictions and to tailor the magnetic properties of a magnetic material is given by growing magnetic superlattices containing two different transition metals. We have here briefly reviewed some recent experimental results on two different superlattice systems Fe/V (001)\textsuperscript{1,2} and Fe/Co (001)\textsuperscript{3} that are and have been extensively studied at the Angstrom Laboratory in Uppsala.\textsuperscript{4,5,11}

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FIG. 3. $M$ vs $H$ for Fe/Co 6/2 and 2/6 along [100] (open circles) and [110] (filled circles) at $T=10$ K, from ref. [3].

FIG. 4. MAE vs Co content for the different Fe/Co (001) samples at $T=10$ K, from ref. [3].

FIG. 5. $M_s$ vs Co content of the different Fe/Co (001) samples at $T=10$ K, from ref. [3].