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Temperature dependence of the interlayer exchange coupling in MBE-grown Fe/Cr/Fe sandwiches

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Abstract

The structure in MBE-grown Fe/Cr/Fe ($d_{Fe} = 40$ Å, 20 Å $< d_{Cr} < 110$ Å) has been investigated with ion beam channeling. The temperature dependence of the interlayer exchange coupling is strongly dependent on the growth temperature of the layers. For the layers grown at 573 K the interlayer exchange coupling is suppressed well below room temperature. This effect is not related to the strain in the Cr layers, which is found to be largely relaxed and only moderately dependent on the growth temperature. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Interlayer exchange coupling; Multilayers

The subject of the magnetism of Cr in the vicinity of Fe layers has been studied extensively over the last years. Recently it was pointed out that the interlayer exchange coupling is highly sensitive to the magnetic properties of the Cr layers and is therefore an excellent testing ground for the various phase transitions which can be observed when varying the Cr thickness or the temperature in Fe/Cr/Fe structures. Fullerton et al. have observed a suppression of the biquadratic coupling below the Néel transition of Cr [1]. With neutron diffraction they probe the Cr layers to have an incommensurate spin density wave magnetism above a critical thickness of 42 Å Cr. Below this thickness their results are consistent with a commensurate Cr phase. Schreyer et al. have observed non-collinear coupling in Fe/Cr superlattices and observed with neutron diffraction a transition from the I-SDW to the C-SDW with increasing temperature for thick Cr layers while for thin Cr layers the C-SDW structure is found [2]. Above the Néel temperature of the C-SDW they observed the suppression of the non-collinear coupling, a transition which was predicted previously by Shi et al. [3]. Here we report on the temperature dependence of the interlayer exchange coupling in Fe/Cr/Fe sandwiches grown epitaxially with MBE. The suppression of the coupling above a critical temperature is found to be strongly dependent on the growth temperature of the layers. For Cr-spacer thickness larger than 60 Å and grown at high temperatures a narrow temperature range exists where coupling is observed. This suppression of the coupling with increasing temperature is not observed in the Fe/Cr/Fe sandwiches grown at lower temperatures where the interlayer exchange coupling is present above room temperature. We show that this effect is not likely to be related to the strain in the Cr layers.

Epitaxial Fe/Cr/Fe sandwiches with constant Fe layer thickness (40 Å) and Cr layer thickness varying between 20 and 110 Å were grown with MBE (base pressure 2×10^{-11} Torr) on MgO (0 0 1). To enhance the mass resolution for the ion beam channeling measurements ^{57}Fe was evaporated from a Knudsen cell at a rate of 0.1 Å/s. Due to the higher mass and the isotopic purity of the ^{57}Fe with respect to natural Fe, the backscattering

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signals of the Fe and Cr layers in such sandwich structures can be easily resolved. Cr was evaporated from an electron beam gun stabilized with a quadrupole massspectrometer set-up at a rate of 0.3 Å/s. Two series of samples were grown at different growth temperatures, 423 and 573 K, respectively. RHEED measurements confirm the epitaxial growth of (0 0 1)Fe,Cr on (0 0 1)MgO with the epitaxial relation [1 1 0]Fe,Cr//[0 1 0]MgO. Fig. 1 shows the random and aligned energy spectrum of 1.97 MeV $^4He^+$ ions backscattered from an Fe/Cr/Fe layer on MgO. The Fe buffer and epilayer can be resolved due to the thick Cr spacer layer. The Cr contribution is separated from the Fe contribution, which allows us to obtain structural information on both Fe and Cr layers. The amount of tetragonal distortion of the individual layers was determined directly from the angular yield profiles of the Fe and Cr signals along the [1 1 1]

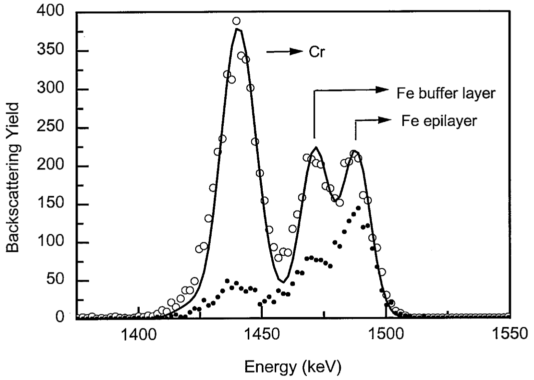

Fig. 1. Random (circles) and aligned (dots) backscattering of an Fe(40 Å/Cr(102 Å)/Fe(40 Å) sandwich epitaxially grown on MgO(0 0 1).

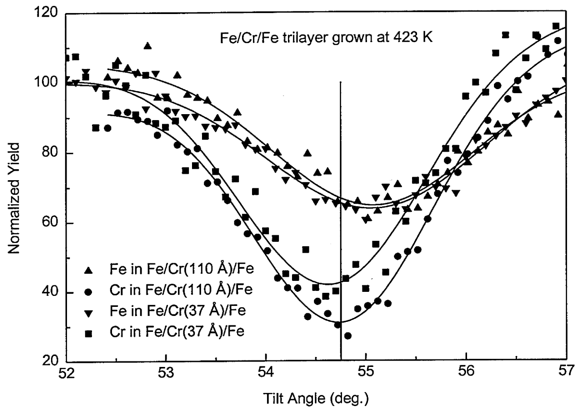

Fig. 2. Angular yield profile for Cr and Fe in Fe/Cr/Fe in the (1 0 0) plane through the [1 1 1] axis. The solid vertical line indicates the position of the cubic [1 1 1] axis.

axis. The strain measurement for layers grown at 423 K are shown for various Cr spacer thickness in Fig. 2. One observes a deviation from the cubic [1 1 1] axis (54.57°) for both the Fe and Cr angular scans. The Fe [1 1 1] axis is at a slightly larger angle from the surface normal which means that the strain is compressive as is expected from the lattice mismatch between the MgO and the Fe. A residual tetragonal distortion is present. The [1 1 1] Fe axis is observed at an angle of 55.06° with respect to the normal [0 0 1] direction while for complete pseudomorphic growth of the Fe on MgO(0 0 1), assuming a Poisson ratio of 0.29, the [1 1 1] axis is expected at 56.66°. The Cr [1 1 1] axis is found at a smaller angle than a [1 1 1] cubic axis which is consistent with a tensile strain. For the layers grown at 423 K the tetragonal distortion decreases with the Cr layer thickness. For a 102 Å thick Cr layer grown at 573 K the tensile strain is larger than for a similar layer grown at 423 K and comparable to the value found for the thin Cr layers grown at 423 K. This is probably due to a difference in tetragonal distortion of the first Fe layer grown at 573 K with respect to 423 K. The Fe layer grown at 573 K is more relaxed. This might be due to a different thermal expansion of the MgO and Fe which for different growth temperatures gives rise to a different strain value.

The interlayer exchange coupling in these Fe/Cr/Fe sandwich structures was investigated with magnetization measurements. Experiments were carried out in an Oxford Instruments vibrating sample magnetometer equipped with a continuous flow cryostat. In Fig. 3 is shown a hysteresis loop measured along the [0 1 0] in-plane axis at 240 K of an Fe(40 Å)/Cr(80 Å)/Fe(40 Å) grown at 423 K. One notices clear jumps in the magnetization when increasing the external field. When lowering the external field from the saturation value the magnetization again shows a discontinuous jump. The loops can be qualitatively explained by a 90° orientation of the Fe layers magnetization. We attribute the typical loop shapes to the presence of interlayer exchange coupling

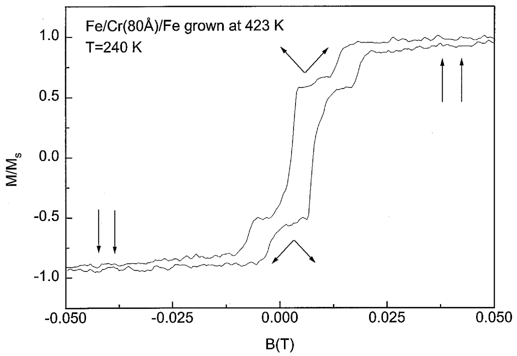

Fig. 3. $M(H)$ loop of an Fe(40 Å)/Cr(80 Å)/Fe(40 Å).

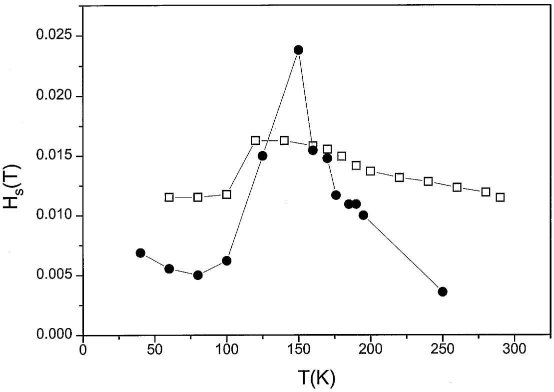

Fig. 4. Temperature dependence of the saturation field for Fe/Cr/Fe sandwich grown at 423 (open aquares) and 573 K (solid circles).

and have used the position of the flip field as a measure of the strength of the interlayer exchange coupling. Fig. 4 shows the temperature dependence of the flip field for two sandwiches grown at 423 K (80 Å Cr) and 573 K (102 Å). One readily notices that the interlayer coupling is only present above a certain temperature. The suppression of the coupling at this temperature has been observed first by Fullerton et al. and attributed to the Néel transition in the Cr spacer layer in sputtered Fe/Cr superlattices [1]. The strength of the coupling decreases much more rapidly with temperature for the layers grown at 573 K than for the layers grown at 423 K. This seems to indicate that the magnetic behaviour of the Cr spacer is very different in both systems. Theoretical results by Shi et al. [3] and subsequent experimental evidence by Schreyer et al. [3] have shown that the coupling in the Fe/Cr system is suppressed above the Néel temperature for thick Cr spacer layers. Although we have no direct measure of the Néel temperature of the Cr in these spacer layers, our results seem to indicate that the Néel temperature is strongly reduced below room temperature for the layers grown at 573 K. It is well known that the Néel temperature of C-SDW Cr can be reduced to similar values by introducing a low concentration of Fe impurities [4]. Interface mixture in Fe/Cr has been observed by Heinrich et al. [5] and is probably the origin for the strong decrease of the coupling with temperature in these Fe/Cr/Fe sandwiches.

In conclusion we have observed a strong variation in the temperature dependence of the interlayer coupling in Fe/Cr/Fe sandwiches grown at various temperatures. Higher growth temperatures result in a smaller tetragonal distortion of the Cr layer so that the strong reduction of the critical temperature for coupling is probably not due to the strain in Cr.

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