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The role of interface alloying on interlayer exchange coupling and the magnetic state of Mn(0 0 1) in Fe whisker/Cr/Mn/Fe(0 0 1) structures

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Abstract

Fe whisker/Cr/Fe(0 0 1) samples can be prepared in a nearly perfect layer by layer growth. It will be shown that the initial reversal of the phase in the short wavelength oscillations of the interlayer exchange coupling is most likely caused by the presence of interface alloying at the Fe/Cr interface. The ability to grow nearly perfect layers of Mn between Cr and Fe layers allows one to investigate the role of a strong intrinsic antiferromagnet, Mn, on the exchange coupling through the weak antiferromagnetic spin density wave in Cr. It will be shown that the Mn layers do not affect the sign of the interlayer exchange coupling. The sign of the exchange coupling is given by the number (parity) of pure Cr atomic layers. These results are consistent with recent theoretical calculations that predict the BCT Mn on Fe is antiferromagnetic with fully compensated (0 0 1) atomic planes.

Keywords: Spin density wave; Exchange coupling; Interlayer alloying; MOKE; BLS

1. Introduction

The magnetic state of Cr(0 0 1) layers sandwiched between Fe(0 0 1) layers (Fe/Cr/Fe) exhibits a transversal intrinsic spin density wave with the wave vector $\boldsymbol{q}$ oriented along the surface normal, and with a short wavelength periodicity of $\lambda = 2.11$ ML [1]. The Cr atoms possess net magnetic moments only in the presence of a spin density wave. The energy required to form a net magnetic moment is positive [2]. It is the negative energy associated with the intrinsic spin density wave that stabilizes the long range magnetic order in Cr. This fact leads to a variety of different magnetic configurations and interlayer exchange couplings in systems that have a high density of atomic steps [3,4].

2. Interface alloying and interlayer coupling

The SFU group has carried out quantitative studies using Fe whisker/Cr/Fe(0 0 1) samples [5–9]. The objectives of the SFU group were to grow samples having the best available interfaces, and to measure quantitatively the strength of the exchange coupling. Our studies showed that the strength of the bilinear exchange coupling J_1 is very sensitive to the initial growth conditions. This behavior led us to believe that the atomic formation of the Cr layer is more complex than had been generally acknowledged. We demonstrated using angular resolved auger electron spectroscopy (ARAES) [9] that atomic interface alloying at the Fe whisker/Cr interface due to an atom interface exchange mechanism played a very significant role and strongly affected the exchange coupling through the Cr spacer. Interface alloying was also observed using STM [10] and proton induced Auger electron spectroscopy [11]. The growth of Fe on Cr is not affected by interface alloying [12,13]; the effect is not symmetric. We suggested [7–9] that the first reversal of

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the phase in the short wavelength oscillations of the exchange coupling in Cr is caused by asymmetric interface alloying. This conclusion is consistent with recent calculations by Freyss et al. [14]. They investigated the phase of exchange coupling for intermixed Fe/Cr interfaces. The calculations were carried out for two mixed layers: Fe(0 0 1)/$Cr_xFe_{1-x}Cr_{1-x}Fe_x/Cr_n$, where n represents the number of pure Cr atomic layers. The calculations were able to account for two important experimental observations. Firstly, the crossover to antiferromagnetic coupling and resumption of the short wavelength oscillations was predicted to occur at 4–5 ML of Cr, in good agreement with our observations [5,6] and NIST studies [1] using the SEMPA imaging technique. Secondly, the change in the phase of the coupling was predicted for x as small as $x = 0.2$. Indeed samples having the Fe/Cr interface prepared at 150°C and showing only a weak interface diffusion ($x \sim 0.2$) [8,9] already exhibited a reversed exchange coupling phase compared with that expected for a perfect interface. The idea that the initial reversal of the phase for the interlayer coupling is caused by interface alloying was further strengthened by using an alloyed Cr–Fe atomic layer during the deposition of the atomic layer in immediate contact with the thin iron film [15]. We showed that for Cr 85–15% Fe and Cr 65–35% Fe the sign of the exchange coupling was not changed, but was given by the number (parity) of the pure Cr atomic layers.

3. Magnetic state of Mn(0 0 1) in Fe/Cr/Mn/Fe

One would expect the behavior of Cr to be modified in a Cr–Mn alloy [16]. Even small concentrations of Mn in Cr result in a strong and commensurate antiferromagnetism. We found that Mn has a very strong tendency for surface segregation during the growth of smooth Cr–Mn alloyed layers. Since the state of the interfaces plays a crucial role in exchange coupling we decided to grow pure atomic layers of Mn between the Cr and Fe layers in order to investigate the role of Mn(0 0 1) in the interlayer exchange coupling. One should point out that the top Cr surface atomic layer is smooth with large atomic terraces (corresponding to those of Fe whiskers) and is unaffected by interface alloying during the deposition of Mn. Therefore, the variations in the exchange coupling, due to additional Mn layers, are primarily dependent on the magnetic state of Mn atoms.

The following samples were studied: (i) Fe/11Cr/1Mn/20Fe(0 0 1), (ii) Fe/11Cr/2Mn/20Fe, (iii) Fe/12Cr/3Mn/20Fe and (iv) Fe/11Cr/3Mn/20Fe. Sample (i) was grown together with Fe/11Cr/20Fe using a shutter thus allowing one to compare the strength of the coupling in samples with and without Mn. MOKE and BLS measurements showed that the sample with 1 ML of Mn, sample (i), did not change the phase of the coupling. The phase was only determined by the number (parity) of Cr atomic layers. However, the coupling strength was significantly enhanced, see Fig. 1. A common view is that the Mn magnetic moment is strongly ferromagnetically coupled to the Fe magnetic moment [19,20] and therefore the sign of the coupling should be unchanged in agreement with the observations. For two atomic layers of Mn, sample (ii), the phase of the coupling was found again to be the same as that for the pure Cr layer, see Fig. 2. The presence of the two Mn layers did not alter the coupling phase even though the second atomic layer of Mn was expected to reverse the sign of the exchange coupling because it should have been AF aligned with respect to the first Mn atomic layer [19,20]. The sample (iii) was ferromagnetically coupled showing that the exchange coupling oscillates with the periodicity of 2 ML and its sign is again only dependent on the parity of Cr layers.

A 3 ML thick Mn, sample (iv), again did not change the sign of the coupling. However, in this case the magnetic moments of the Fe layers were oriented perpendicularly, non-collinearly, in the ground state, $H = 0$, see Fig. 1. Note that the Mn layers in our samples do not

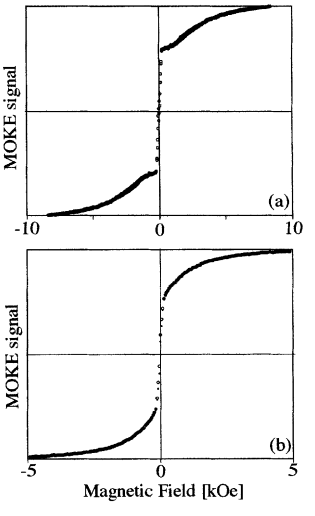

Fig. 1. The magnetisation along the applied external field: (a) Fe/11Cr/1Mn/20Fe/20Au(0 0 1). A bilinear exchange coupling $J_1 = -1.7$ erg/cm^2, and a biquadratic exchange coupling $J_2 = 0.55$ erg/cm^2. The exchange coupling was increased by a factor of 2.5 compared to that without Mn. (b) Fe/11Cr/3Mn/20Fe/20Au(0 0 1). $J_2 = 0.8$ erg/cm^2, $J_1 \ll J_2$. J_1 and J_2 are bilinear and biquadratic exchange couplings, respectively. The rapid change in the MOKE signal around $H = 0$ corresponds to the remagnetization process of the Fe whisker. The exchange coupling was described by bilinear and biquadratic terms, $\varepsilon_{exch} = -J_1 \cos(\theta) + J_2 \cos^2(\theta)$, where θ is the angle between the magnetic moment of the Fe thin film and the surface magnetic moment of the Fe whisker. J_1 and J_2 were calculated by using the theory [17] which includes the non-collinear distribution of the saturation magnetization $\boldsymbol{M}$ inside the Fe whisker.

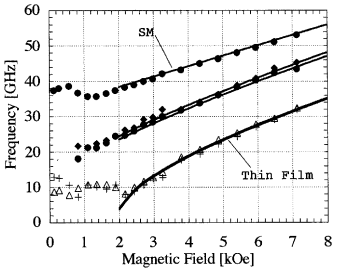

Fig. 2. Frequency vs. applied magnetic field measured for the low-lying spin-wave modes using Brillouin light scattering (BLS) and a composite specimen Fe whisker/11Cr/2Mn/20Fe/20Au(0 0 1). Frequencies were measured using 514.5 nm laser light in the back-scattering configuration, and incident on the specimen at 45°. (●) – surface mode (SM) and down-shifted bulk edge mode; (◆) – up-shifted bulk edge mode frequency; (+) – down shifted thin film frequency, and (△) – up-shifted thin film frequency. The solid lines were calculated using the formalism described by Cochran [18]. The magnetic parameters used for the bulk Fe were $4\pi M_s = 21.4$ kG, cubic anisotropy $K_1 = 4.76 \times 10^5$ erg/cm^3, and the uniaxial surface anisotropy $K_s = 0.5$ erg/cm^2. The magnetic parameters used for the Fe film were $4\pi M_s = 21.4$ kG, $K_1 = 3.5 \times 10^5$ erg/cm^3, and $K_s = 1.0$ erg/cm^2 (two surfaces included). The thin film was antiferromagnetically coupled to the bulk Fe through the total interlayer exchange coupling $J_{tot} = J_1 - 2J_2 = -0.9$ erg/cm^2. From the low-field ($H < 1$kOe) thin film frequencies one finds $J_{tot} = -0.33$ erg/cm^2 when the bulk and thin film magnetizations are antiparallel. From these two exchange coupling values one obtains a bilinear exchange coupling $J_1 = -0.62$ erg/cm^2 and a biquadratic exchange coupling $J_2 = 0.14$ erg/cm^2.

affect the sign of the coupling, and therefore the non-collinear configuration of the magnetic moments in sample (iv) can not be blamed easily on interface roughness [21].

The assumption that the magnetic state of Mn in Fe/Cr/Mn/Fe(0 0 1) structures can be described by commensurate antiferromagnetism with uncompensated (0 0 1) planes is not necessarily correct. In recent calculations by Krueger et al. [22] the magnetic structure of BCT Mn in bulk was studied as a function of the tetragonal distortion, c/a. The calculations showed that the BCT Mn grown on Fe(0 0 1) has a magnetic state that is at the border line between the AF1 configuration having the magnetic moments parallel in the (0 0 1) planes and the AF3 (1 1 0) configuration having the ferromagnetic planes oriented along (1 1 0) and with fully compensated (0 0 1) planes having zero net magnetic moment. The calculations showed that the lowest energy state is just marginally the AF3(1 1 0) state, only 4 mV/atom lower than the AF1 state. The AF3(1 1 0) state would not lead to an alternating sign of exchange coupling with increasing Mn thickness as was experimentally observed. The above calculations show that independence of the sign of the exchange coupling on Mn thickness is not at variance with expectations based on the bulk BCT Mn structure on Fe(0 0 1). This view is further supported by recent theoretical and experimental studies. Wu and Freeman [23] showed that one atomic layer of Mn on Fe(0 0 1) is compensated (ordered antiferromagnetically). Recent experimental studies using magnetic circular X-ray dichroism (MCXD) [24,25] showed no net magnetic moment for higher Mn coverages on Fe(0 0 1). These results are again consistent with the conclusion that the Mn(0 0 1) atomic planes are antiferromagnetically ordered and magnetically compensated.

In conclusion, we found that Mn atomic layers deposited between Cr(0 0 1) and Fe(0 0 1) in Fe whisker/Cr/Fe(0 0 1) structures did not affect the phase of the short wavelength oscillations in the interlayer exchange coupling. The sign of the coupling was determined by the number (parity) of Cr atomic layers. This result is consistent with recent theoretical and experimental predictions that the ground state of BCT Mn is composed of magnetically compensated (0 0 1) planes. However, the onset of non-collinear coupling with increasing Mn thickness looks like an intrinsic property of thicker BCT Mn layers, and detailed calculations for the Fe/Cr/Mn/Fe(0 0 1) system would be desirable.

References

[1] D.T. Pierce, J.A. Stroscio, J. Unguris, R.J. Celotta, Phys. Rev. B 49 (1994) 14 564.
[2] D. Stoeffler, F. Gautier, NATO ASI Ser. B: Physics, vol. 39, Plenum Press, New York, 1993, p. 411.
[3] E.E. Fullerton, K.T. Riggs, C.H. Sowers, S.D. Bader, Phys. Rev. Lett. 75 (1995) 330.
[4] P. Bodeker, A. Hucht, A. Schreyer, J. Borchers, F. Guthoff, H. Zabel, Phys. Rev. Lett. 81 (1998) 914.
[5] B. Heinrich, M. From, J.F. Cochran, L.X. Liao, Z. Celinski, C.M. Schneider, K. Myrtle, Proceedings of MRS Spring Meeting, vol. 313, 1993, p. 119.
[6] B. Heinrich, J.F. Cochran, Adv. Phys. vol. 42, 1993, p. 523.
[7] B. Heinrich, J.F. Cochran, D. Venus, K. Totland, D. Atlan, S. Govorkov, K. Myrtle, J. Appl. Phys. 79 (1996) 4518.
[8] B. Heinrich, J.F. Cochran, D. Venus, K. Totland, C. Schneider, K. Myrtle, J. Magn. Magn. Mater. 156 (1996) 215.
[9] D. Venus, B. Heinrich, Phys. Rev. B 53 (1996) 1733.
[10] A. Davies, J.A. Stroscio, D.T. Pierce, R.J. Celotta, Phys. Rev. Lett. 76 (1996) 4175.
[11] R. Pfandzelter, T. Igel, H. Winter, Phys. Rev. B 54 (1996) 4496.
[12] P.J. Schurer, Z. Celinski, B. Heinrich, Phys. Rev. B 51 (1996) 2506.
[13] W. Keune, Mossbauer studies using Fe/Cr and Cr/Fe interfaces, unpublished.
[14] M. Freyss, D. Stoeffler, H. Dreysse, Phys. Rev. B 56 (1997-II) 6047.

[15] B. Heinrich, J.F. Cochran, T. Monchesky, K. Myrtle, J. Appl. Phys. 81 (1997) 4350.
[16] E. Fawcett, H.L. Alberts, V.Yu. Galkin, D.R. Noakes, J.V. Yakhmi, Rev. Mod. Phys. 66 (1994) 25.
[17] J.F. Cochran, J. Magn. Magn. Mater. 137 (1995) 101.
[18] J.F. Cochran, J. Magn. Magn. Mater. 169 (1997) 1.
[19] T.G. Walker, H. Hopster, Phys. Rev. B 48 (1993) 3563.
[20] S. Bouarab, H. Nait-Laziz, M.A. Khan, C. Demangeat, H. Dreysse, M. Benakki, Phys. Rev. B 52 (1995) 10 127.
[21] J.C. Slonczewski, J. Magn. Magn. Mater. 150 (1995) 13.
[22] P. Krueger, O. Elmouhssine, C. Demangeat, J.C. Parlebas, Phys. Rev. B 54 (1996-I) 6393.
[23] R. Wu, A.J. Freeman, Phys. Rev. B 51 (1995) 17 131.
[24] O. Rader, W. Gudat, D. Schmitz, C. Carbone, W. Eberhardt, Phys. Rev. B 56 (1997) 5053.
[25] J. Dresselhaus, D. Spanke, F.U. Hillebrecht, E. Kisker, G. van der Laan, J.B. Goedkoop, N.B. Brookes, Phys. Rev. B 56 (1997) 5461.