Layered magnetic structures: Antiferromagnetic-type interlayer coupling and magnetoresistance due to antiparallel alignment

P. Grünberg, S. Demokritov,[a] A. Fuss, M. Vohl, and J. A. Wolf
Forschungszentrum Jülich, IFF, Postfach 1913, D-5170 Jülich, Federal Republic of Germany

Layered Fe/Cr structures are known to display antiferromagnetic-type interlayer coupling and a new magnetoresistance (MR) effect due to antiparallel magnetization alignment. The strength of the coupling is found to be similar in multilayered structures and in double layers. The oscillatory behavior of the coupling, previously found by Parkin, More, and Roche [Phys. Rev. Lett. **64**, 2304 (1990)] on sputtered polycrystalline samples, is here confirmed for epitaxial samples, obtained by thermal evaporation. The new MR effect is interpreted as due to a spin-dependent scattering of the electrons at the Fe-Cr interfaces. The investigations have been extended to Fe/V, Fe/Mn, Fe/Cu, Co/Au, Co/Cr, and Co/Cu structures where the antiparallel alignment of the ferromagnetic layers is obtained via hysteresis effects. A MR effect due to antiparallel alignment, which is strong for Co/Au and Co/Cu but weak in the other cases, has been found.

Layered Fe/Cr structures display antiferromagnetic (AF) -type interlayer coupling[1–7] at room temperature and a new magnetoresistance (MR) effect[5–11] due to antiparallel magnetization alignment of adjacent ferromagnetic films. We would like to present here our most recent measurements confirming the oscillatory behavior of the coupling found first by Parkin, More, and Roche[7] and extending their data to the ranges of ferromagnetic (F) -type interlayer exchange which alternate with those of AF-type exchange. We also review the data found in other laboratories and in other systems where AF-type interlayer coupling has been found so far. Furthermore we will give an overview of the data obtained in our laboratory on the MR effect due to antiparallel magnetization alignment which also includes data from other systems. This demonstrates that AF-type interlayer coupling is not a necessary precondition for the new MR effect.

Because of the limited space we can only indicate a few important details about the experiments. Most of them were performed on sandwich structures, i.e., two ferromagnetic films of thickness d interspaced by a nonferromagnetic film of thickness d_0. For the investigation of the coupling phenomena we mainly used samples with wedge-type interlayers. This has the advantage that a continuous range of interlayer thicknesses can be studied on one sample with identical magnetic films. The different interlayer thicknesses can be investigated by scanning the focused probing laser beam across the sample. The $M(H)$ curves can then be observed point by point via the magneto-optical Kerr effect (MOKE) and the spinwaves are detected by a frequency analysis of the inelastically scattered light. For the Fe/Cr system particular attention was also given to good epitaxial growth. It was achieved by *e*-gun evaporation onto (100)-type GaAs substrates that had been coated before by epitaxial Ag buffer layers, using well-known receipes.[12] More on the growth will be reported at a later date.

In the following we would like to denote film thicknesses by d_M where M is the film material. For a layered structure of material A with material B we use the notation $\mathrm{A}_{d\mathrm{A}}/\mathrm{B}_{d\mathrm{B}}$ where the thicknesses dA, dB are given in nm. The type of growth is indicated either by the type of atomic plane parallel to the sample plane [e.g., (100)] or by the growth direction (e.g., [100]).

Essentially there are two experiments from which values for the size of the AF-type interlayer coupling can be deduced. These rely on the spin-wave properties of the layered structure and the behavior during magnetization reversal, or the $M(H)$ curve.

For a quantitative evaluation of the exchange interaction of ferromagnetic films across an interface the interface exchange energy is written in the form[13]

$$E_s = -2A_{12}\frac{\mathbf{M}_1\cdot\mathbf{M}_2}{|\mathbf{M}_1||\mathbf{M}_2|}. \tag{1}$$

Here $\mathbf{M}_1$, $\mathbf{M}_2$ are the saturation magnetizations of the two films and E_s denotes the energy per surface unit of interface. Instead of A_{12} often another parameter J is used where $J = 2A_{12}$.

The parameter A_{12} defined by Eq. (1) can be deduced from $M(H)$ curves by measuring the field B_s where the samples saturate parallel to the external field, against the torque due to AF-type coupling. It is clear that by this method only negative A_{12} (AF coupling) can be determined, for positive A_{12} there is no equivalent torque. For AF-type coupling for sandwiches we obtain

$$A_{12} = -B_s M(d/4), \tag{2}$$

where M and d are, respectively, the magnetization and thickness of the ferromagnetic films. [For multilayers the factor of 4 on the right-hand side of Eq. (2) has to be replaced by 8, or simply replace A_{12} by J in Eq. (2)].

Figure 1 shows, on the right-hand side, hysteresis curves from Fe5/Crd_{Cr}/Fe5 sandwiches for different Cr thicknesses as indicated. Nonrectangular hysteresis curves indicate AF-type coupling and the parameter A_{12} can be evaluated from the saturation field B_s as indicated. The sample with $d_{\mathrm{Cr}} = 0.6$ nm due to too strong AF-type coupling could not be saturated by the available external field,

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[a] Permanent address: Institut for Physical Problems, Moscow, USSR.

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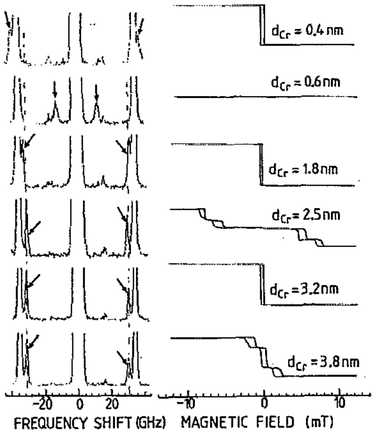

FIG. 1. BLS spectra and hysteresis curves of $Fe_{d_{Fe}}/Cr_{d_{Cr}}/Fe_{d_{Fe}}$ sandwich structures with d_{Fe} = 5 nm and different Cr thicknesses d_{Cr}. For the BLS experiments the external field B_0 = 0.5 T was along the hard axis. Note that for d_{Cr} = 0.6 nm only a small portion of the total sheared $M(H)$ curve is displayed.

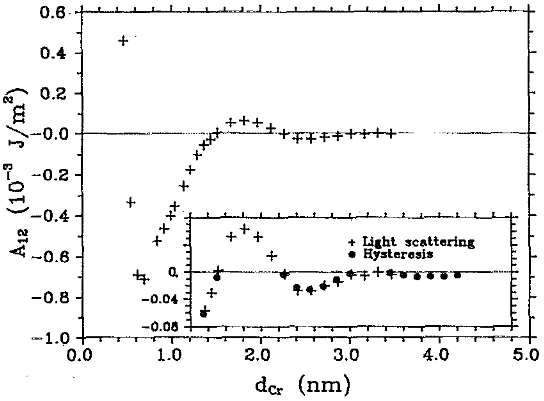

FIG. 2. Interlayer exchange constant A_{12} as a function of d_{Cr} for samples as in Fig. 1. Data points obtained from BLS (+), and from $M(H)$ (□). The fit was obtained with the following parameters: $A = 2.1 \times 10^{-11}$ J/m, $g = 2.1$, $M = 1671$ kA/m, $K_{os} = 0.8 \times 10^{-3}$ J/m^2, $K_v = 4.0 \times 10^4$ J/m^3. The insert relates to the same abscissa as the main part but the ordinate is stretched.

hence in this case B_s and A_{12} could not be determined. We take here the A_{12} value from a previous experiment with larger d_{Fe}.

The other method of obtaining quantitative information on the interlayer exchange is via the observation of spin-wave modes. So far the method is restricted to double layers because of the complexity of the mode spectra in multilayers. A detailed description of the method has been given elsewhere[14] (see also Ref. 4). The spin-wave modes can be detected by means of microwave absorption or Brillouin light scattering (BLS). On the left-hand side of Fig. 1 we display BLS spectra from the same samples used on the right-hand side. There are two modes, which appear both on the Stokes (S) and the anti-Stokes (AS) side. The mode that occurs in all spectra at $\approx \pm 35$ GHz is called the acoustic or Damon Eshbach (DE) mode and is independent of the interlayer exchange. It can be used to test whether the various regions of the samples with the wedged interlayers are magnetically identical except for the interlayer exchange. As seen from the displayed spectra this is the case within the experimental uncertainty. The other mode, which in Fig. 1 is marked by arrows, is sensitive to the interlayer exchange and called the optical mode. Its calculated position for zero coupling is marked on the S and AS side by vertical dashed lines. The other features seen in these spectra are partly ghosts and are unimportant in the present context. We see that AF-type coupling shifts the optical mode below the position representing the decoupled case which is in agreement with theory.

To apply the theory one has to choose, for the magnetic materials, values for various parameters such as magnetization M, g factor, exchange constant A, volume anisotropy K_v, and surface anisotropy at the outer surfaces K_{os}. From spectra as in Fig. 1 we obtain then the $A_{12}(d_{Cr})$ dependence. The result is displayed in Fig. 2 together with the data obtained from the $M(H)$ curves. It confirms the observation reported first by Parkin and coworkers[7] that the interlayer coupling oscillates as a function of the Cr thickness. We complete the results given by these authors here by reporting for the first time also the values of positive A_{12} between the ranges of AF-type coupling, as determined by means of BLS. The oscillations of the optical mode in the spectra of Fig. 1 for d_{Cr} = 0.6–3.2 nm are clearly seen but they are not too much above the experimental error. This is why they have escaped detection in previous work employing BLS. For the detection of the AF coupling range around d_{Cr} = 3.8 nm the resolution of BLS here is still insufficient, although the effect is clearly seen in the $M(H)$ curve. Further increase of the resolution of BLS, however, is possible and is currently pursued.

It is interesting to compare the strength of the AF coupling in the cases reported so far, including other systems. In Table I, which is taken from Ref. 15 we have compiled our values for A_{12} in comparison with values obtained from the literature. Only the maximum value for each system is reproduced. The data obtained from the multilayers and the sandwiches are reasonably consistent.

For the Fe-Cr structures it has been found that the antiparallel alignment in small fields goes along with a remarkable increase in the electrical resistivity.[5–11] It was also reported that similar increases of the resistivity are also observed in other layered structures if antiparallel alignment is achieved. For this we do not necessarily need the existence of AF-type interlayer coupling: the antiparallel aligned configuration can also be obtained via hysteresis effects.[9]

If we denote the resistivity in the parallel aligned state by $\rho\uparrow\uparrow$ and in the antiparallel aligned state by $\rho\uparrow\downarrow$ then $\Delta\rho/\rho\uparrow\uparrow = (\rho\uparrow\downarrow - \rho\uparrow\uparrow)/\rho\uparrow\uparrow$ is the quantity of interest. In Table I we have compiled our data on the new MR effect together with values taken from the literature. In those cases where the entry under A_{12} is zero the antiparallel aligned state was obtained via the hysteresis effect.

The absolute change in resistivity $\Delta\rho$ is found to be approximately independent of temperature.[9] The increase of $\Delta\rho/\rho\uparrow\uparrow$ at low temperatures is mainly due to the decrease of $\rho\uparrow\uparrow$. This indicates that the source of the MR effect is temperature independent. Further evidence comes from the observation that in Fe/Mn and in Fe/V in con-

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TABLE I. Data for interlayer exchange constant A_{12} and relative resistivity change $\Delta\rho/\rho$ due to antiparallel alignment (in the literature, e.g., Refs. 3–7, often a parameter $J=2A_{12}$ is used). The notation for the samples quotes the material and its thickness in units of nm.

Sample	T (K)	A_{12} (erg/cm^2) (10^{-3} J/m^2)	$\Delta\rho/\rho$ (%)	Growth	Ref.
Fe10/Cr0.5/Fe10	300	-0.6	···	epitax. (100)	15
Fe10/Cr0.5/Fe10	4.2	-0.9	···	epitax. (100)	15
Fe12/Cr1/Fe12	300	···	1.5	epitax (110)	15
Fe12/Cr1/Fe12	10	···	4.1	epitax. (110)	15
[Fe12/Cr1]$_4$Fe12	300	···	2.8	epitax. (110)	15
[Fe12/Cr1]$_4$Fe12	10	···	13.8	epitax. (110)	15
[Fe3/Cr0.9]$_{40}$	300	$-$ 1.0–1.3^a	···	epitax. (100)	6
[Fe3/Cr0.9]$_{40}$	4.5	$-$ 1.5–2.0^a	185^b	epitax. (100)	5 and 6
Fe4/Cr1.6/Fe4	300	-0.18	1	epitax. (100)	2
[Fe2/Cr0.7]$_{20}$	4.5	-0.8	33	polycr.	7
Fe0.7/Cu1.7/Fe1.5	295	-0.11	···	epitax (100)	3 and 4
Fe0.7/Cu1.8/Fe1.3	77	-0.12	···	epitax (100)	3 and 4
Co10/Cr0.8/Co10	300	-0.05	<0.1	polycr.	15
[Co1.5/Cr0.4]$_{30}$	···	-0.16	2.5	polycr.	7
[Co2/Ru0.3]$_{20}$	300	-2.5	···	polycr.	7
[Co2/Ru0.3]$_{20}$	4.5	···	6.6	polycr.	7
Fe12/Cr0.8/Fe12	300	-0.35	···	polycr.	16
Fe10/Cr0.8/Py10^c	300	-0.08	···	epitax. (100)-polycr.	15
Co10/Au4/Co10	300	0	1.8	polycr.	15
Co10/Au4/Co10	4.5	0	2.7	polycr.	15
Co10/Cu5/Co10	300	0	2.0	polycr.	15
Co10/Cu5/Co10	4.5	0	6.5	polycr.	15
Fe10/Mn3.5/Fe10	300	0	0.02	polycr.	15
Fe10/V1.6/Fe10	300	0	0.25	polycr.	15
Fe10/V1.6/Fe10	4.5	0	0.5	polycr.	15
Fe10/Cu6/Fe10	300	0	0.5	polycr.	15
Fe10/Cu6/Co10	300	0	1.6	polycr.	15

[a] Depending on the value assumed for M_s.

[b] Note our definition of $\Delta\rho/\rho$ which differs from the one used in Refs. 5 and 6.

[c] Py = $\mathrm{Ni_{0.8}Fe_{0.2}}$ (Permalloy).

trast to Fe/Cr, $\Delta\rho$ is rather small (see Table I). Therefore the scattering responsible for $\Delta\rho$ should be due to impurities or roughness and should take place at the internal interfaces or in the interlayer. With these assumptions we have performed an analysis of the effect in Fe/Cr and found good agreement between experiment and theory.[9]

The observation that the size of the MR effect for different Cr interlayer thicknesses is approximately proportional to the value of the interlayer exchange constant A_{12} suggests that there is an intimate link between the two phenomena.[7,10,11] On the other hand, as we have discussed there are also experimental examples of a strong MR effect in systems with no detectable AF-type coupling. Therefore, it is likely that the two effects are generally independent but in particular cases as in Fe/Cr, modifications of magnetic and electronic properties at interfaces can lead both to AF-type coupling and the new MR effect.

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