Oscillatory Exchange Bias Effect in FeNi/Cu/FeMn and FeNi/Cr/FeMn Trilayer Systems

T. Mewes – University of Kaiserslautern

B. F. P. Roos – University of Kaiserslautern

S. O. Demokritov – University of Kaiserslautern

B. Hillebrands – University of Kaiserslautern

Citation of published version:

Mewes, T., Roos, B., Demokritov, S., Hillebrands, B. (2000): Oscillatory Exchange Bias Effect in FeNi/Cu/FeMn and FeNi/Cr/FeMan Systems, *Journal of Applied Physics*, 87(9).
https://doi.org/10.1063/1.373249

Oscillatory exchange bias effect in FeNi/Cu/FeMn and FeNi/Cr/FeMn trilayer systems

T. Mewes, B. F. P. Roos, S. O. Demokritov,[a] and B. Hillebrands
Fachbereich Physik und Schwerpunkt Materialwissenschaften, Universität Kaiserslautern, Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany

The first experimental observation of a spacer-thickness dependent oscillatory exchange bias effect in ferromagnet(FM)/spacer/antiferromagnet trilayers is reported. The period of the oscillatory exchange bias field is found to be half of the period of the oscillatory interlayer coupling in the corresponding FM/spacer/FM systems with the same spacer, indicating that the observed effect is caused by an analogous coupling mechanism, being, however, sensitive to the absolute value of the coupling strength and not on its sign.
[S0021-8979(00)59608-X]

Exchange coupling between a ferromagnetic (FM) and an antiferromagnetic (AF) layer at their mutual interface was under intensive investigation in the past decades, since it is believed to play an important role in the exchange bias effect.[1–3]

On the other hand, in 1986 it was discovered that magnetic interlayer exchange coupling between two FM layers can be mediated by a nonmagnetic spacer layer.[4] The coupling was later found to oscillate as a function of the spacer thickness[5] changing its sign between FM and AF coupling.[6,7]

Recently the exchange bias effect has been investigated in trilayers, where a FM FeNi and an AF CoO layer were separated by a nonmagnetic spacer—Cu, Ag, and Au.[8] The authors have observed a long-range exchange coupling decreasing exponentially across the spacer.

We report the first experimental observation of an oscillatory exchange bias field in a FM/spacer/AF layered system. We find that the exchange bias field, measured on high quality $Fe_{20}Ni_{80}/Cu/Fe_{50}Mn_{50}$ and $Fe_{20}Ni_{80}/Cr/Fe_{50}Mn_{50}$ trilayer systems, oscillates as a function of the thickness of the spacer.

Still up to today the details of the microscopic origin of the exchange bias effect, especially the exact magnetic structure of the AF layer near the FM/AF interface,[9–11] are under debate. To discuss the effects reported in our work, it is sufficient to use a simple picture proposed first by Mauri *et al.*[2] and Malozemoff:[3] while the FM layer is in a single domain state forced by an external field, the AF layer grown on top is formed in nascendi in a multidomain state, since the local interaction between the FM and the AF layer shifts locally the equilibrium between different, otherwise energetically degenerated AF domains. After completion of growth the magnetic structure of the AF layer persists (if not too strong magnetic fields are applied)—one now needs a given field, H_{eb}, to remagnetize the FM layer, i.e., the hysteresis curve is shifted along the field axis.

The above mechanism provides exchange biasing independently of whether the FM-AF interaction is ferromagnetic or antiferromagnetic. The sign of the interaction only defines which particular AF domain is energetically preferable for a given orientation of the magnetization of the FM layer.[3,10] For the following let us classify these domains as (+) domain for the case of the FM-type interaction and (–) domain for the AF-type interaction. Usually, it is almost impossible to determine experimentally the sign of the FM/AF interface interaction.[12]

The trilayers were prepared in an ultrahigh vacuum (UHV) evaporation system (5×10^{-10} mbar base pressure). All samples were grown on chemically cleaned, thermally oxidized $5\times10\,mm^2$ Si/SiO_2 substrates at $T_{sub}=200\,°C$ with 100-Å-thick $Fe_{50}Mn_{50}$ or Cr buffers, and they were covered by a 20-Å-thick Cr-cap layer to prevent oxidation. The FeNi and FeMn layers were prepared with a constant thickness of 50 and 100 Å , while the Cu and the Cr spacers were grown in a wedge shape geometry (wedges 0–8 Å). The chemical analysis of the prepared films was performed *in situ* by a calibrated Auger electron spectrometer. An external magnetic field of 50 Oe saturating the FM layer was applied along the film plane of the samples during the entire preparation process.

The sample hysteresis loops were studied at RT using a magneto-optical Kerr effect magnetometer. The values of H_{eb} were determined form the shift of the loops, and for the samples without any nonmagnetic spacer $H_{eb}\approx 80-100$ Oe depending on the buffer material. The exchange bias field H_{eb} of the samples Si/SiO_2/100 Å FeMn/50 Å FeNi/d_{Cu}Cu/100 Å FeMn/20 Å Cr is plotted in Fig. 1 as a function of d_{Cu}. The shifted hysteresis loops of three samples with different d_{Cu}, demonstrating the exchange bias effect, are also shown in the inset of Fig. 1. The uncertainty in the determination of the H_{eb} indicated by the error bars is ±1 Oe. It is clear from Fig. 1 that the exchange bias field rapidly decreases with increasing spacer thickness d_{Cu}. However, in addition to monotonic decay the experimental data shown in Fig. 1 demonstrate an oscillatory behavior. The difference between the experimental values of H_{eb} and the exponentially decaying background dependence, indicated in Fig. 1 by a dash line is presented in Fig. 2 versus d_{Cu}. It clearly reveals an oscillatory contribution of H_{eb}. The result of the fit: $H_{eb}\propto\exp(-d/L)|\cos(2\pi(d/\lambda)-\phi)|$ with

[a]Electronic mail: demokrit@physik.uni-kl.de

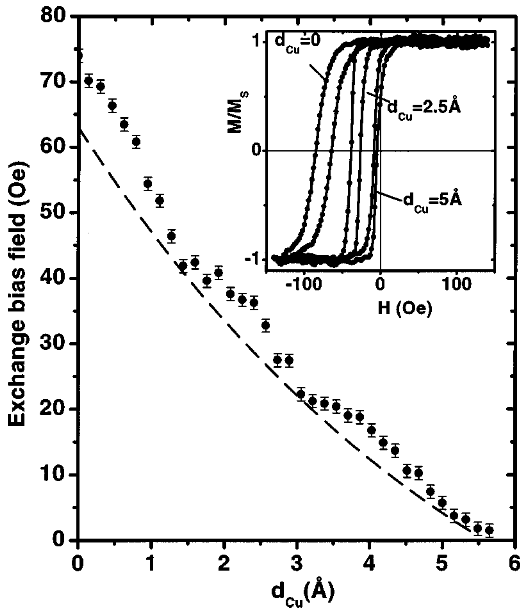

FIG. 1. The dependence of the exchange bias field H_{eb} in a trilayer system of the composition FeNi/Cu/FeMn on the Cu spacer layer thickness d_{Cu}. The dash line indicates the exponentially decaying monotonic background, used for data processing as described in the text. In the inset the shifted hysteresis loops of the FeNi/Cu/FeMn samples for some values of d_{Cu} are shown.

the decay length of the oscillation amplitude $L=6$ Å, the oscillation wavelength $\lambda=3.9$ Å, and the phase shift $\phi=49°$ is also shown in Fig. 2. Note here that both the measured and the calculated dependencies demonstrate damped oscillations with a quasiperiodicity of $\lambda/2=1.45$ Å.

In the trilayer system with a Cr spacer the exchange bias field shows a very similar behavior. Using the same fit procedure one obtains for the FeNi/Cr/FeMn system: $L=3.5$ Å, $\lambda=2.2$ Å $\phi=21°$, and the quasiperiodicity $\lambda/2=1.1$ Å.

Thus, the found oscillatory exchange bias field is a general phenomenon, the oscillation periods being dependent on the spacer material. One possible explanation for this are periodic variations of the interface morphology which can cause cosine-type oscillations of the magnetic anisotropy as

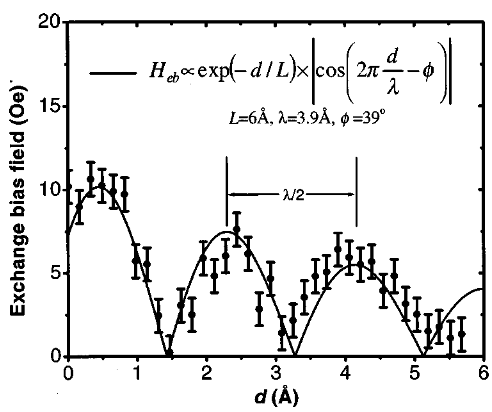

FIG. 2. The oscillating part of the exchange bias field H_{eb} in the trilayer system of the composition FeNi/Cu/FeMn versus the Cu spacer layer thickness d_{Cu}. The solid line represents the result of the fit. Note that the fit function has a quasiperiodicity of $\lambda/2$.

observed for ultrathin Co films[13] analogously to the intensity variations in reflection high-energy electron diffraction (RHEED). By assuming a monotonic dependence of the exchange bias field on the interface roughness, as observed by Lederman *et al.*[14] for FeF_2/Fe bilayers or by Shen and Kief[15] for NiO/NiFe bilayers, it is to expect that a periodic variation of the interface morphology will cause a cosine-type variation of H_{eb}. Experimentally the oscillating part of $H_{eb}(d)$ does not follow a simple cosine function, as it is most clearly illustrated by its kink-type behavior near the zeros. Also note here that the investigated samples are polycrystalline.

To explain the above experimental findings, we propose another model relating the oscillatory exchange bias field to the oscillatory interlayer coupling, well known in layered system, containing two ferromagnetic layers and a nonmagnetic spacer.[5–7,16] As described above, the exchange bias effect in a FM-AF layered system is caused by the FM-AF interface exchange interaction. If a nonmagnetic spacer is placed between the FM and AF layers, in analogy to the FM/spacer/FM system, the effective field induced by the FM layer in the AF layer will oscillate as a function of the spacer thickness, likely due to the quantum well effect for conduction electrons in the spacer.[17] There is no exchange biasing for those thicknesses where this oscillating function passes zero, since here the FM and AF layers do not interact. If the coupling strength is nonzero, the exchange bias caused by this indirect interaction is independent of the sign of the interaction. Thus, if the interaction depends on the spacer thickness as $\cos(2\pi d/\lambda)$, the exchange bias field should be a function of its absolute value, $H_{eb}(|\cos(2\pi d/\lambda)|)$ and an oscillatory dependence of H_{eb} on d with a period of $\lambda/2$ should be observed.

Since for both Cr and Cu spacers the interlayer coupling demonstrates short period oscillations with periods of about 2 ML (2.5 and 3.9 Å for Cr and Cu, respectively),[6,7] the exchange bias fields will then oscillate with periods of about 1 ML (1.25 and 1.85 Å correspondingly). These values are very close to the experimentally observed periodicities.

As it is seen in Fig. 1 the observed oscillatory dependence $H_{eb}(d)$ has a relatively small amplitude, decreasing with the thickness, and it is superimposed on a monotonic decaying background function. To understand the origin of the reduced oscillation amplitude and of the monotonic background, one needs to consider more closely the influence of short- and long-range fluctuations of the spacer thickness (with the crossover between them being determined by the exchange correlation length in the AF layer, ξ) on the magnetic order of the FM/spacer/AF trilayer.

In a qualitative approach let us first consider a model system, where the spacer possesses only short-range variations of its thickness with the amplitude δ. These variations cause changes of the sign of the interaction between the FM and the AF layer across the spacer. However, in a similar way as it is in the fluctuation mechanism of the biquadratic coupling,[18] small areas of a given type of the interaction cannot create different types of the AF domains. Only domains with typical lateral sizes larger than ξ will be created. Their types $[(+)$ or $(-)]$ are defined by the value of the interaction, $\overline{J}$, averaged over the domain size. $\overline{J}$, in turn, is determined by the average value of the spacer thickness, as well as by δ. It is zero, if $\delta \gg \Lambda$, where Λ is the period of the oscillatory interaction. In this case no exchange bias should be observed. If $\delta \lesssim \Lambda$, the average interaction is not zero. It changes periodically with the average value of the spacer thickness, reflecting the oscillatory nature of the microscopic interaction.

Long-range variations of the spacer thickness have a different influence on the exchange bias effect. These variations cause long-range variations of $\overline{J}$ and H_{eb}. However, during formation of the magnetic structure of the AF layer the FM layer was saturated. Therefore, the *same* orientation of **M** is stored in all AF domains independently of the sign of the FM-AF interaction. It means, the exchange bias effect will not be washed out by the averaging process over the long-range variations, even if their amplitude Δ is large compared to Λ. A macroscopic exchange bias field, although *monotonically* depending on the spacer thickness, should be observed. In the intermediate case $\Delta \approx \Lambda$ one obtains a superposition of the oscillatory and the monotonic behavior. We emphasize here, that Δ and δ characterize the variations of the spacer thickness, but not the entire roughness of the interfaces. A quantitative comparison between the morphology of the interfaces of the trilayers and the dependence $H_{\mathrm{eb}}(d)$ is beyond the scope of this article and is the topic of future studies.

In conclusion, we have investigated layered systems, where exchanged coupled ferromagnetic and antiferromagnetic layers were separated by a nonmagnetic (Cu or Cr) spacer layer. For the first time an exchange bias field, which oscillates as a function of the spacer thickness, is experimentally observed. The observed oscillation period, as well as a characteristic shape of the oscillation are explained on the basis of a proposed model, connecting this effect with the oscillatory interlayer coupling across the spacer.

This work was supported by the Deutsche Forschungsgemeinschaft.

[1] W. H. Mejklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956).
[2] D. Mauri, H. Siegman, P. S. Bagus, and E. Kay, J. Appl. Phys. **62**, 3047 (1987).
[3] A. P. Malozemoff, J. Appl. Phys. **63**, 3874 (1988).
[4] P. Grünberg, R. Schreiber, Y. Pang, M. B. Brodksy, and H. Sowers, Phys. Rev. Lett. **57**, 2442 (1986).
[5] S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).
[6] S. Demokritov, J. A. Wolf, and P. Grünberg, Europhys. Lett. **15**, 881 (1991); P. Grünberg, S. Demokritov, A. Fuss, R. Schreiber, J. A. Wolf, and S. T. Purcell, J. Magn. Magn. Mater. **104–107**, 1734 (1992).
[7] Z. Celinski and B. Heinrich, J. Magn. Magn. Mater. **99**, L25 (1991).
[8] N. J. Gökemeijer, T. Ambrose, and C. L. Chien, Phys. Rev. Lett. **79**, 4270 (1997).
[9] N. C. Koon, Phys. Rev. Lett. **78**, 4865 (1997).
[10] T. J. Morgan, J. Nogues, D. Lederman, and I. K. Schuller, J. Appl. Phys. **72**, 617 (1998).
[11] T. C. Schulthess and W. H. Butler, Phys. Rev. Lett. **81**, 4516 (1998).
[12] J. Nogues, D. Lederman, T. J. Morgan, and I. K. Schuller, Phys. Rev. Lett. **76**, 4524 (1996).
[13] W. Weber, C. H. Back, A. Bischof, Ch. Würsch, and R. Allenspach, Phys. Rev. Lett. **76**, 1940 (1996).
[14] D. Lederman, J. Nogues, and I. K. Schuller, Phys. Rev. B **56**, 2332 (1997).
[15] J. X. Shen and M. T. Kief, J. Appl. Phys. **79**, 5008 (1996).
[16] S. S. P. Parkin, Phys. Rev. Lett. **67**, 3598 (1991).
[17] P. Bruno, Phys. Rev. B **52**, 411 (1995); M. D. Stiles, J. Appl. Phys. **79**, 5805 (1996).
[18] J. C. Slonczewski, Phys. Rev. Lett. **67**, 3172 (1991).