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

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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.

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 grown in an UHV-evaporation system (5×10^{-10} mbar base pressure). All samples were grown on chemically cleaned, thermally oxidized $5 \times 10 mm^2$ Si/SiO_2 substrates with 100 Å thick $Fe_{50}Mn_{50}$ or Cr buffers, and they were covered by 20 Å thick Cr-cap layer to prevent oxidation. To improve the sample quality the films were grown at $T_{sub} = 200^o C$. Results obtained on the trilayer, where Cu and FeMn were deposited at room temperature, will be also shown to demonstrate the sensitive dependence of the magnetic properties on the growth temperature. The better quality of the samples prepared at elevated temperature is not only attested by their pronounced oscillatory exchange bias field (see below), but also by their much smaller coercive field, H_c. The samples prepared at room temperature show a coercive field of H_c = 70 Oe, whereas those prepared at $T_{sub} = 200^o C$ show H_c = 40 Oe. Smaller coercive fields are a clear indication of a smaller concentration of defects in the systems prepared at elevated temperature.

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 was applied along the film plane of the samples during the entire preparation process.

The sample magnetization loops were studied at RT using a magnetooptical Kerr effect magnetometer. The values of H_{eb} for the samples without any nonmagnetic spacer are about 80-100 Oe depending on the buffer material and the growth temperature. With increasing spacer thickness, d, the exchange bias field decays very fast. The value of the decay length depends on both the spacer material and the growth temperature. It is in any case smaller than the value observed in [8] and it is in the range of 2-6 Å.

The best prepared systems demonstrate an oscillating contribution to $H_{eb}(d)$ in addition to the monotonic decay. This is shown in Fig. 1, where H_{eb} of two samples of the same composition of Si/SiO_2/100ÅFeMn/50ÅFeNi/ d_{Cu}Cu /100ÅFeMn/20ÅCr are plotted versus d_{Cu}. Open circles in Fig. 1 denote the sample prepared at T_{sub} =RT, and the full circles the sample prepared at $T_{sub} = 200^oC$. Already the raw data shows an oscillatory contribution on top of the monotonically decaying background. The oscillatory contribution is illustrated in detail in the inset of Fig. 1. Here only the oscillatory part of the dependence is presented together with the results of the fit to this part: $H_{eb} \propto exp(-d/L)|cos(2\pi\frac{d}{\lambda} - \phi)|$ with the decay length of the oscillation amplitude $L = 6$ Å, the oscillation wavelength $\lambda = 3.9$ Å, and the phase shift $\phi = 49^o$.

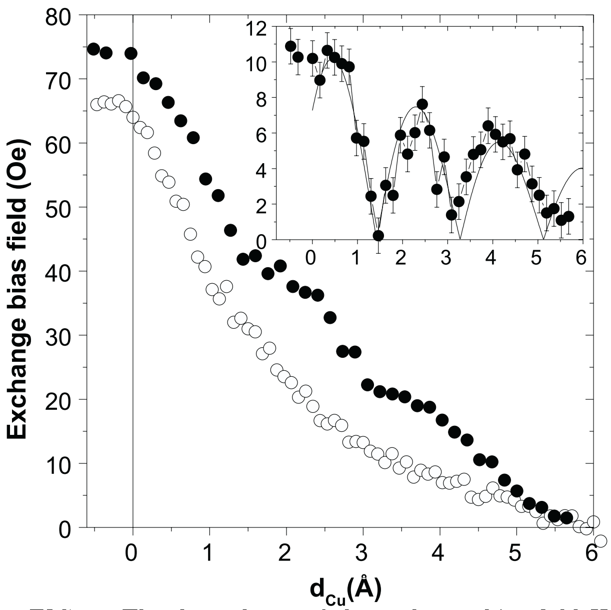

FIG. 1. The dependence of the exchange bias field H_{eb} in two trilayer systems of the composition FeNi/Cu/FeMn on the Cu spacer layer thickness d_{Cu}. ∘ -the sample prepared at T_{sub} =RT, • - the sample prepared at $T_{sub} = 200^oC$. The vertical line at $d_{Cu} = 0$ indicates the begin of the Cu wedge, $d_{Cu} < 0$ corresponds to the double layer system FeNi/FeMn and is used as a reference. In the inset the oscillatory part of $H_{eb}(d_{Cu})$ together with the fit curve is shown.

In the trilayer system with a Cr spacer the exchange bias field shows a very similar behavior. Using the same fit function we obtain for the FeNi/Cr/FeMn system: $L = 3.5$ Å, $\lambda = 2.2$ Å and $\phi = 21^o$.

This demonstrates that 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 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 [14] for FeF_2/Fe bilayers or by Shen [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.

Thus, to understand the above experimental findings, we relate 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 Å 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 Å 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. This, at least at the first glance, contradicts to the model, presented above, which predicts an oscillatory dependence only. To understand the origin of the reduced oscillation amplitude and of the monotonic background, we need to consider more closely the influence of the variations of the spacer thickness on the magnetic order of the FM/spacer/AF trilayer. These variations cannot be characterized by a single parameter, like, e.g., the mean squared thickness variation, since their lateral scale plays a decisive role in the formation of the experimentally measurable exchange bias field. In this sense the variations can be divided into short-range and long-range variations, the crossover between them being determined by the exchange correlation length in the AF layer, ξ. The exchange correlation length roughly determines the smallest lateral size of the domains.

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 as it is shown in Fig. 2a. 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. Domains with typical lateral size l, $l \gtrsim \xi$ will be created. Their types ((+) or (−)) are defined by the value of the interaction, $\bar{J}$, averaged over l. $\bar{J}$, 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 (as it is illustrated in Fig. 2b), reflecting the oscillatory nature of the microscopic interaction. The decreasing amplitude of the oscillation is caused by an increasing function $\delta(d)$.

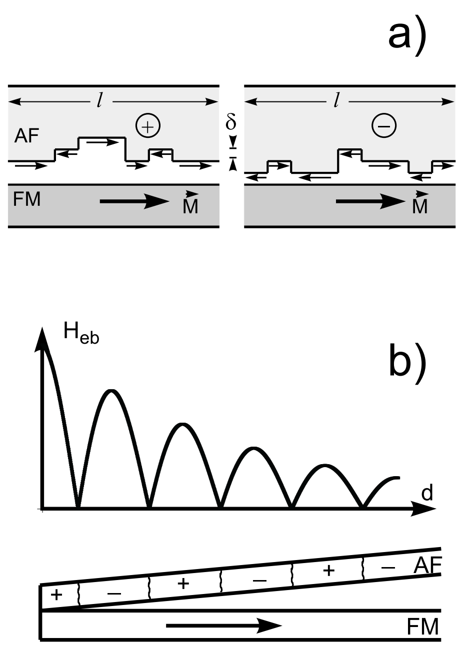

FIG. 2. (a) Schematic side view of ferromagnet/spacer/antiferromagnet trilayer possessing short-range variations of the spacer thickness. The arrows near the spacer/antiferromagnet interface indicate the orientation of local effective fields induced by the ferromagnetic layer across the spacer. Right: $\bar{J} > 0$, i.e., the average effective field is parallel to the magnetization of the feromagnetic layer, $\vec{M}$, promoting (+) AF domains; left: $\bar{J} < 0$, i.e., the field is antiparallel to $\vec{M}$, promoting (−) AF domains. δ is the amplitude of the variations. l is the domain size, which determines the lateral scale of averaging. (b) Expected dependence of the exchange bias field, H_{eb} on the spacer thickness, d. (+) and (−) signs indicate the intervals of d having positive or negative $\bar{J}$, correspondingly.

Long-range variations of the spacer thickness have a different influence on the exchange bias effect. These variations cause long-range variations of $\bar{J}$ and H_{eb}. But, since in all cases the *same* orientation of $\vec{M}$ is stored in the AF layer, 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 $H_{eb}(d)$ is beyond the scope of this paper 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.

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