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Letter to the Editor

# Local exchange bias observed by photoemission microscopy

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**Abstract**

By using a photoemission electron microscope in combination with X-ray magnetic circular dichroism, the domain configuration in a single crystalline Co film exchange coupled to an $Fe_{50}Mn_{50}$ film is obtained. The effect of the ferromagnetic/antiferromagnetic interaction is observed to be different in Co domains with different magnetization direction, establishing the fact that the exchange bias is locally set by the magnetization of the ferromagnetic layer, without external field.
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One of the phenomena that has attracted a great deal of interest in the field of thin film magnetism is, in recent years, the interaction between a ferromagnetic (FM) and an antiferromagnetic (AFM) material. As it has been discovered in the 1950s [1], this interaction may lead to a unidirectional anisotropy, dubbed exchange anisotropy, which induces, among other effects, a shift of the hysteresis loop along the applied field axis. The amount of the shift is referred to as exchange bias field, since the displaced hysteresis loop can be described by considering the presence of an additional external field which biases the system. The application of this effect in spin valve devices [2,3] and the intriguing difficulty in unraveling the microscopic origin of the magnetic interaction at the FM/AFM interface has led to a large number of investigations, both experimental and theoretical (see Refs. [4,5], for reviews).

Typically, unidirectional anisotropy is found in FM/AFM bilayer systems if the AFM material is grown in an external applied field ($H_{ext}$) or if the system is cooled from above the Néel temperature ($T_N$) of the antiferromagnet in an external applied field (field cooling procedure). In a simple interpretation one may consider that $H_{ext}$ sets the exchange bias direction. Experiments by Miltényi et al. on $FeF_2$/Fe and Co/CoO samples [6] indicate actually that the role of $H_{ext}$ in a field cooling procedure is only to ensure a uniformly magnetized state for the FM layer,[2] and that it is possible

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[2] As pointed out in Ref. [6] this is true until one considers values of $H_{ext}$ large enough to saturate the FM layer, but small enough not to affect the AFM layer, possibly leading to the observation of the so-called *positive* exchange bias [7].

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to tune the value of the exchange bias field by cooling in zero field from different remanent magnetization states of the ferromagnet. Similar findings have also been reported by Gökemeijer et al. [8]. As inferred in Ref. [6], the orientation of the magnetization in the ferromagnetic domains, present in the not-saturated FM layer during cooling through $T_N$, would determine locally the exchange bias direction in the area of the domains, leading to a shifted hysteresis loop according to the relative amount of one or the other type of domains. On the other hand a direct link has been found between the FM and the AFM domains in $Co/LaFeO_3$ interacting bilayers: local exchange bias has been observed in some of the smaller magnetic domains of the Co film deposited on top of antiferromagnetic $LaFeO_3$, and claimed to be due to a surplus of uncompensated spins in the individual AFM domains which are frozen in after growth [9].

In order to locally explore the effect of the magnetization of the FM layer in establishing the exchange bias, we planned a very simple experiment, i.e., the deposition of the AFM layer on top of a not-saturated FM film in the as-grown state. The exchange interaction at the interface should establish in this case different preferred directions in the AFM domains formed during growth on top of FM domains with different magnetization orientation, provided there is some kind of interface coupling between the FM and the AFM layer. The magnetic domain configuration of the buried FM layer is then explored by photoemission electron microscopy in combination with X-ray magnetic circular dichroism, which allows a local and element selective investigation of the magnetic structure. By using a well defined system, namely single crystal Co/FeMn bilayers [10], we demonstrate in this letter that the bias direction is set by the magnetization of the FM layer, observing the exchange bias effect locally in the domain configuration of the FM Co film exchange coupled to the AFM $Fe_{50}Mn_{50}$ film. As a consequence, the response to an external field is observed to be different in ferromagnetic domains with different magnetization orientation.

The experiments were performed in an ultra high vacuum chamber with a base pressure of $10^{-8}$ Pa, where $Co/Fe_{50}Mn_{50}$ bilayers were epitaxially grown at room temperature in zero field by electron beam assisted thermal evaporation on a Cu(0 0 1) single crystal substrate. Details on the structural and magnetic properties of the $Co/Fe_{50}Mn_{50}$ bilayers on Cu(0 0 1) are given elsewhere [10]. The bilayers were grown as crossed double wedges, as described in a previous publication [11], resulting in approximately 120 μm wide wedges separated by a plateau of uniform film thickness at the upper end of the wedges. Magnetic domain images were obtained at room temperature by using a photoemission electron microscope (PEEM) from the asymmetry of the local secondary electron intensity at the Co $L_3$ absorption edge upon helicity reversal of circularly polarized excitation. The magnetic contrast is thereby provided by magnetic circular dichroism after excitation with X-rays, delivered at the UE56-2/PGM2 beamline of the Berlin synchrotron radiation facility BESSY. Since the local magnetic information is carried to the PEEM by low-energy secondary electrons, the magnetic domain image one obtains during the application of an even small external field is typically too much defocussed, due to the influence of the magnetic field on the electron's trajectory. Nevertheless, it is still possible to study the influence of a magnetic field on a domain configuration by recording the image after the external field has been applied and switched off. In the experiments presented here, a pulsed magnetic field parallel to the sample surface was obtained by discharging a capacitor through a core-less solenoid placed close to the sample stage of the PEEM. The measurements were carried out always at zero field.

A local exchange bias effect in the Co domain configuration may be observed when the $Fe_{50}Mn_{50}$ film coupled to the Co film is in an AFM phase. A thickness dependent transition from paramagnetic to AFM in an $Fe_{50}Mn_{50}$ film coupled to a Co film has been identified from the steep rise in the coercive field of the $Co/Fe_{50}Mn_{50}$ bilayers when the $Fe_{50}Mn_{50}$ film exceeds $\approx 10$ ML at room temperature [10]. At the same $Fe_{50}Mn_{50}$ thickness an abrupt change in the Co domain configuration has been imaged by PEEM, for both Co deposited on top of $Fe_{50}Mn_{50}$ or covered by it [12]. By recording images after application of an external field one can fully correlate these two observations. The result of this experiment is shown in Fig. 1. The Co domain pattern in a Co/$Fe_{50}Mn_{50}$ crossed double wedge sample deposited on Cu(0 0 1) is imaged by the PEEM in the as grown state in Fig. 1(a), and after application of field pulses of different values in Figs. 1(b) and (c). The $Fe_{50}Mn_{50}$ thickness ($t_{FeMn}$) increases from bottom to top in the images as indicated at the left axes, and the Co thickness ($t_{Co}$) from left to right as indicated at the bottom axis. Both thicknesses are given in units of atomic monolayers (ML). A sketch of the sample is shown on the left of the figure. The crystallographic axes and the direction of the incoming X-rays ($h\nu$) are indicated. The grey double arrow displays the positive ($+H$) and the negative ($-H$) directions of the applied field. In Fig. 1(a) one can notice a characteristic domain pattern for Co grown on an $Fe_{50}Mn_{50}$ wedge. The magnetization direction, displayed by arrows in some domains, always lies in the plane of the film and is found along one of the $\langle 1\,1\,0 \rangle$ azimuth axes for $t_{FeMn} < 10$ ML. This is also the easy axis of magnetization of a Co film directly grown on Cu(0 0 1) [13,14]. The many small domains present for $t_{FeMn} > 10$ ML are a signature of the antiferromagnetic state of the $Fe_{50}Mn_{50}$ film for this thickness range, as discussed in Ref. [12]. The same sample area as in Fig. 1(a) is displayed in Fig. 1(b) after the application of a 15 Oe field pulse along the negative ($-H$) direction. For $t_{FeMn} < 10$ ML the magnetization has switched from the [1 1 0] direction to the [$\bar{1}\,\bar{1}\,0$] direction. The region of the Co film coupled to $Fe_{50}Mn_{50}$ thicker than 10 ML remains unaffected by the field pulse.[3] This reflects the behavior of the coercive field in these two $Fe_{50}Mn_{50}$ thickness regions, as reported in Ref. [10]. Pulsed magnetic fields up to a maximum of $+260$ Oe have then been applied before recording image (c). Here the magnetization at $t_{FeMn} < 10$ ML has reverted back to the same direction as in Fig. 1(a). The Co domain configuration has also changed for some domains at $Fe_{50}Mn_{50}$ thicknesses between 10 and 13 ML. Where now the bright area is present in place of the small domains the magnetization could be directed along the [0 1 0] azimuth direction, the easy axis of magnetization for a thin Co film coupled to AFM $Fe_{50}Mn_{50}$ [12]. Actually, since the area is so small, the statistics is not good enough to draw definite conclusions. One can notice that the changes in Fig. 1(c) with respect to Fig. 1(a) are more prominent at the higher Co thickness side. This is due to the decrease in coercive field upon increasing the Co thickness [10].

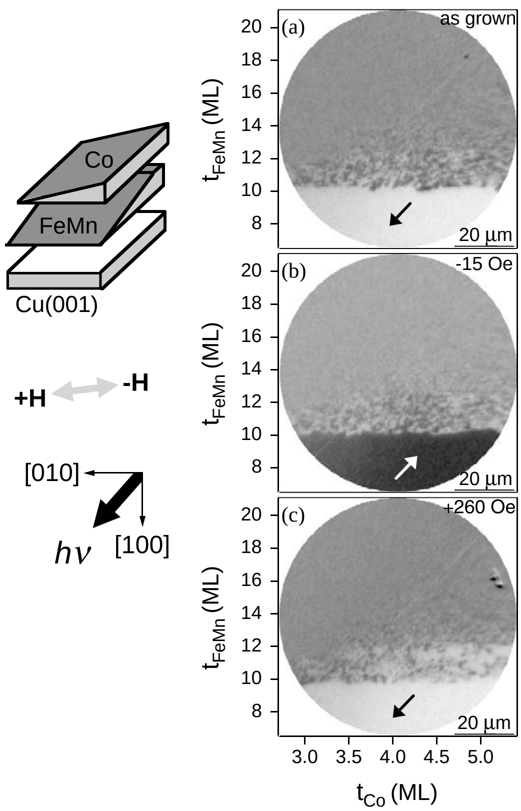


Fig. 1. Changes in the Co domain configuration in a Co/$Fe_{50}Mn_{50}$/Cu(0 0 1) sample by application of an external field. Thicknesses are indicated at the axes of the images. Magnetization direction is indicated by arrows in some domains. The sketch on the left shows the double wedge structure of the sample. Crystallographic axes, incoming X-rays ($h\nu$) and external magnetic field ($H$) directions are indicated.

[3] A close look at Fig. 1 actually reveals that the black dot present in the upper right part of Fig. 1(a) has disappeared in Fig. 1(b). The black dot is in reality a defect on the sample surface, more prominent in Fig. 1(a) for example because of a small difference in x-ray intensity for opposite helicity.

The observation of a local exchange bias effect may be done at an $Fe_{50}Mn_{50}$ thickness greater than 10 ML, when the alloy film is expected to be in an AFM state at room temperature. As considered before, if the $Fe_{50}Mn_{50}$ film is grown on top of an FM Co film, then the bias direction should be defined by the magnetization direction of the Co film, and should be different in magnetic domains with different magnetization orientations. Such a situation is realized in the domain image shown in Fig. 2(a). Here the Co domain configuration in the as-grown state is reported from an $Fe_{50}Mn_{50}$/Co/Cu(0 0 1) double wedge sample. The six images of Fig. 2 display the same sample area, where the $Fe_{50}Mn_{50}$ and the Co thicknesses are indicated at the left and bottom axes, respectively. Crystallographic axes, incoming X-rays ($h\nu$) and external magnetic field ($H$) directions are indicated. The sample in the as-grown state, imaged in Fig. 2(a), displays a big grey domain for $t_{FeMn} < 10$ ML with magnetization oriented along the $[1\,\bar{1}\,0]$ direction. For $Fe_{50}Mn_{50}$ thicknesses bigger than 10 ML, a dark region on the left of the image and a bright region on the right are present. The bright and dark region in Fig. 2(a) were most likely oppositely magnetized domains before deposition of $Fe_{50}Mn_{50}$ on top of the Co film. Since after the deposition of an AFM $Fe_{50}Mn_{50}$ film the magnetization direction changes by $+/-45^\circ$ from $\langle 1\,1\,0 \rangle$ to $\langle 1\,0\,0 \rangle$ directions [12], a pattern of $90^\circ$ domains is weakly visible inside the two regions. In images (b)–(f) of Fig. 2 a contour plot of the domain pattern of Fig. 2(a) is superimposed, displayed by white lines. The contrast of the contour plot has been set in a way that just the difference between the large dark and bright regions can be recognized. The grey domain for $t_{FeMn} < 10$ ML is therefore ignored since it does not contribute to any local exchange bias, as mentioned before. A field of $-330$ Oe is first applied. Most part of the sample area, Fig. 2(b), is now dark, although not saturated. For thicknesses above $t_{FeMn} \approx 19$ ML the domain pattern is not affected by the application of the field, probably

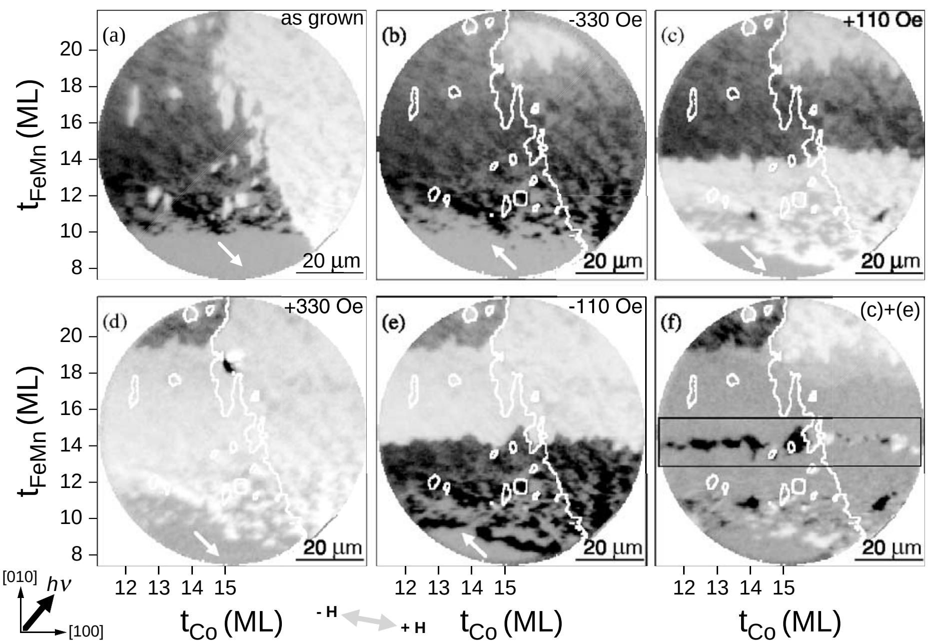


Fig. 2. Observation of local exchange bias effect in a $Fe_{50}Mn_{50}$/Co crossed wedges bilayer grown on Cu(0 0 1). Images display the Co domain pattern: (a) in the as-grown state; (b)–(e) after application of magnetic fields as indicated; (f) sum of (c) and (e), showing local exchange bias in the region enclosed by the rectangle. In (b)–(f) a contour plot of the domain pattern of (a) is shown superimposed. Co and $Fe_{50}Mn_{50}$ thicknesses are indicated at the bottom and left axes of the images, respectively. Crystallographic axes, incoming X-rays ($h\nu$) and external magnetic field ($H$) directions are indicated.

due to the increase in coercivity of the Co/ $Fe_{50}Mn_{50}$ bilayer by increasing $t_{FeMn}$. A field of +110 Oe [Fig. 2(c)] reverts the bottom part of the image to bright. In particular one can see, with the help of the contour plot of the as-grown state, that the bright region has extended to higher $Fe_{50}Mn_{50}$ thickness in the right part of the image compared to the left part. This is consistent with the domain pattern of Fig. 2(a): the external field is more effective in switching the magnetization to the "bright" direction in the region that was bright during growth of the AFM layer than it is in the region that was dark in the as-grown state. This observation can be explained considering that the AFM $Fe_{50}Mn_{50}$ film growing on Co has acquired a preferred magnetization direction at the interface that points prevalently into the "bright" or "dark" direction according to the bright or dark region of Co in the as-grown state. As a consequence, if the external field is applied along the "bright" (positive) direction, a larger area will be switched to bright on the right of the contour plot, as observed in Fig. 2(c), since here also the AFM $Fe_{50}Mn_{50}$ interface moments are pointing into the "bright" direction. On the contrary the external field applied along the positive direction is less effective in switching the magnetization on the left of the contour plot in Fig. 2(c), where the AFM $Fe_{50}Mn_{50}$ film is biasing the Co into the "dark" direction. Therefore, due to the local exchange bias, the bright region can be more easily reversed where it was already present in the as-grown state.

After a field pulse of +330 Oe [Fig. 2(d)] the opposite domain configuration as in Fig. 2(b) is obtained: now the imaged sample area is almost totally bright. The subsequent field of −110 Oe [Fig. 2(e)] has the same strength but opposite direction than the field that created Fig. 2(c). Considering the above discussion one would expect a configuration symmetric to that of Fig. 2(c), that is, having the dark region extending to higher $Fe_{50}Mn_{50}$ thickness on the left-hand side of the image where the dark region was present in the as-grown state. Actually the effect is here less clear than in Fig. 2(c), suggesting that the coupling at the interface between the FM and the AFM layer, responsible for the exchange bias effect, is weaker on the right of the contour plot than on the left. This difference is hard to be explored from the present data, and may arise from slightly different interaction of the growing FeMn film with the magnetic Co underlayer. In order to confirm the local exchange bias, the sum of images (c) and (e) has been calculated. The result is shown in Fig. 2(f). Since a dark contrast corresponds to negative values of the asymmetry and a bright contrast to positive ones, the image has an intermediate grey scale contrast (values of summed asymmetry around zero) for those areas that exhibit opposite contrast in Figs. 2(c) and (e). The topmost part of Fig. 2(f) is bright on the right hand side and dark on the left-hand side. These are the areas that remained unchanged with respect to the as-grown state, because there the coercivity is higher than 330 Oe. The interesting area is the one enclosed by the black rectangular box where a kind of irregular dark/bright horizontal stripe is visible, surrounded by a region of intermediate grey scale contrast. One sees that this stripe is mostly dark on the left of the contour plot line, and mostly bright on the right, which means that the area of the stripe on the left (right) of the contour plot has not been reached by the white (black) region in Fig. 2(c) [Fig. 2(e)], but has already been reached by the black (white) region in Fig. 2(e) [Fig. 2(c)]. In other words, the result of Fig. 2(f) indicates that the field of 110 Oe, applied in opposite directions before acquiring Figs. 2(c) and (e), rotates the magnetization of the Co film in a way which depends on the magnetization orientation of the as-grown state [Fig. 2(a)]: (i) the +110 Oe field has switched the magnetization to bright more easily in the region where the bright region was present in the as-grown state, as one can see from the bright stripe on the right of the contour plot in Fig. 2(f); (ii) on the contrary the −110 Oe field switches the magnetization orientation from bright to dark more easily in the region which was already dark in the as-grown state, resulting in the dark stripe observable in Fig. 2(f) inside the rectangular box on the left of the contour plot. The fact that the dark area in the rectangular box is greater than the white area indicates, as discussed before, that the exchange bias from the left contour is greater than that from the right contour.

The result is, therefore, consistent with the bias directions imposed by the dark and bright regions of the as-grown state, and the effect can be explained as arising from local exchange bias. In fact since each of the two regions was saturated in an opposite direction, the AFM $Fe_{50}Mn_{50}$ film grown on them acquires an opposite orientation of the exchange bias in the two domains, where the field necessary to set the bias direction is supplied by the Co magnetization, and the bias direction is opposite in the two domains. Locally, that is in each of the two domains, an opposite asymmetric behavior upon applying the external field has, therefore, been observed.

In conclusion, by using a photoemission electron microscope, the domain configuration in Co/$Fe_{50}Mn_{50}$ bilayers has been obtained in the as-grown state and after application of external fields. An exchange bias effect has been observed locally in the different Co domains, since the magnetization appears to be pinned in different directions by the exchange interaction with the AFM $Fe_{50}Mn_{50}$ film. This result demonstrates that exchange bias is set locally by the magnetization of the FM film, without an applied external field.

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