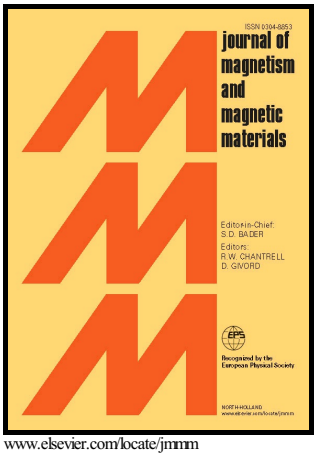
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Kerr microscopy study of exchange-coupled FePt/Fe exchange spring magnets

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Abstract

Magnetization reversal and magnetic microstructure of top soft magnetic layer (Fe) in exchange spring coupled $L1_0$ FePt/Fe is studied using high resolution Kerr microscopy. With remnant state of the hard magnetic layer ($L1_0$ FePt) as initial condition, magnetization (M-H) loops along with magnetic domains are recorded for the top soft magnetic layer (Fe) using Kerr microscopy. Considerable shifting of Fe layer hysteresis loop from center which is similar to exchange bias phenomena is observed. It is also observed that one can tune the magnitude of hysteresis shift by reaching the remanent state from different saturating fields (H_{SAT}) and also by varying the angle between measuring field and H_{SAT}. The hysteresis loops and magnetic domains of top soft Fe layer demonstrate unambiguously that soft magnetic layer at remanent state in such exchange coupled system is having unidirectional anisotropy. An analogy is drawn and the observations are explained in terms of established model of exchange bias phenomena framed for field-cooled ferromagnetic - antiferromagnetic bilayer systems.

Key words: Exchange spring magnets, exchange bias, magnetic domains, Kerr microscopy

1. Introduction

Exchange bias (EB) phenomena occurs due to unidirectional anisotropy induced across the ferromagnetic (FM) antiferromagnetic (AFM) interfaces when the system is field-cooled through the *Néel* temperature (T_N) of the AFM. EB phenomena manifests as a shift of hysteresis loop along the field axis[1]. Various applications of these materials such as permanent magnets, recording media, spin-valves etc., are demonstrated [1]. Since EB phenomena involves a complicated interfacial magnetic interaction between FM and AFM layers different magnetization reversal processes are observed [1]. In most of the cases asymmetric shaped hysteresis loops are observed. Different methods such as Lorentz microscopy, Kerr microscopy etc., are used to study the magnetic domain evolution in such FM-AFM exchange biased systems [2, 3]. Asymmetry in hysteresis loop or magnetic microstructure is found to be different from system to system, in some cases even it is almost negligible [4]. Typically, for the asymmetric loops, two magnetization reversal mechanisms are observed viz., coherent rotation, nucleation and domain wall propagation [3].

Field cooling through the T_N of AFM layer sets a prebiasing of some interface moments, which essentially imposes a shift of the hysteresis loop associated to the FM layer along the field axis generally in the opposite direction to the cooling field [1]. This shift i.e., EB phenomena decreases as a function of temperature and repeated application of magnetic field (known as training

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effect) at a given temperature. The temperature at which shift becomes zero i.e., the point at which EB phenomena disappears is usually called the blocking temperature (T_B). For example, in Co-CoO based compounds which are extensively explored in literature, T_N is 290 K and T_B is found to be as low as 200 K and therefore limiting their room temperature (RT) based application capability [1]. Whereas T_B values for metallic AFM layers such as $Fe_{50}Mn_{50}$ are found to be above RT and are more attractive [1]. Therefore, from an application point of view, the system should exhibit EB phenomena at and above RT.

Recent studies indicate that such shifting of hysteresis loops is not only restricted to FM-AFM system but can also be observed in exchange spring magnets consisting magnetic layers with different magnitude of coercive fields [5, 6, 7, 8]. The advantage of exchange spring magnets as compared to FM-AFM systems is that one need not to field cool the samples across T_N for obtaining EB phenomena and are functional even at room temperatures. Apart from this, exchange spring magnets consisting of soft magnetic (SM) and hard magnetic (HM) phases are the focus of current research because of various technological applications such as permanent magnets with high energy product, ultra-high density recording etc [9, 10]. Therefore, one could see lot of advantages of such exchange spring structures with induced unidirectional anisotropy. However, one of the main disadvantage could be the large stray field induced by the pinning HM layer.

Berger et al., have studied extensively the exchange bias phenomena in SM layers coupled to HM (CoCr soft layer exchange coupled via a Ru interlayer with a hard magnetic CoPtCrB layer) using bulk magnetization measurements [6, 7, 8]. The SM layer is expected to have a uni-directional anisotropy in such SM/HM systems resulting in EB phenomena [1]. Therefore the response of the SM layer and also the evolution of magnetic microstructure is different as compared to individual and un-biased SM layers. Kerr microscopy is one technique which can give both magnetization and magnetic microstructure in a single measurement and therefore is being used extensively in recent times [11, 12]. Present work reports the Kerr microscopy investigation of FePt/Fe bilayer prepared by ion beam sputtering and show that top soft Fe layer at remanent state in such exchange coupled system exhibits unidirectional anisotropy.

2. Experimental

FePt/Fe bilayer film with the structure FePt(30nm)/Fe(22nm)/C(2nm) is deposited by ion beam-sputtering and detailed structural, magnetic and exchange spring behavior are reported in ref [13]. The $L1_0$ phase of FePt layer is obtained by thermal annealing [13]. The magnetic domains were imaged by high resolution magneto-optical Kerr microscope (M/s Evico Magnetics, Germany) and the magnetization (M-H) loops were measured simultaneously by deriving the magnetization signal from the average domain image intensity [11, 12]. The measurements are carried out in longitudinal and transverse mode. For the sake of comparison, Kerr microscopy measurements are also carried out on Fe film of about 22 nm thickness deposited on silicon substrate.

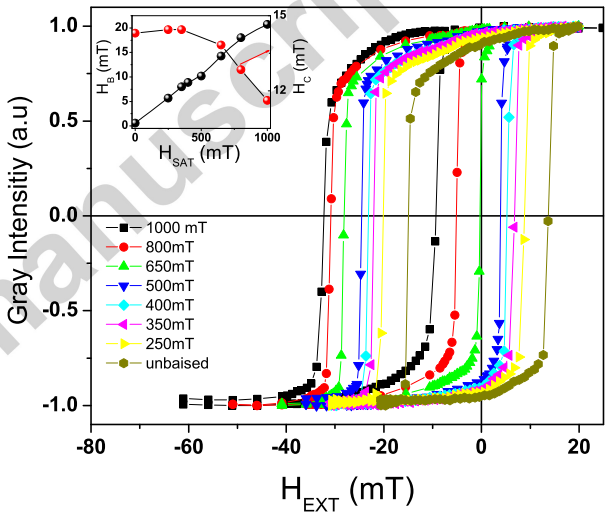


Figure 1: Longitudinal MOKE hysteresis loops of Fe layer in FePt/Fe sample measured at remanent state approached from different saturating fields (H_{SAT}). Note the horizontal shift (H_B) of loops. Unbiased correspond to the case when remanence approached with H_{SAT} made to zero in oscillating mode. Inset shows variation of shift (H_B) and coercivity (H_C) with H_{SAT}. Solid line is guide to eye.

3. Results and Discussions

Figure-1 shows hysteresis loops of the soft Fe layer measured at remanent state approached from different saturating fields. To reach remanent state the FePt/Fe bilayer was initially subjected to a given external field (for example 1000 mT henceforth designated as H_{SAT}, saturation field used for reaching remanent state) and then slowly H_{SAT} was made to zero. For the subsequent

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measurement with another H_{SAT} the sample was subjected to an oscillating zero field. As one can see from Figure-1, the loops are shifted to negative side when the remanent state was approached from positive H_{SAT}. Reverse behavior i.e., shifting of loop to positive side is observed when the remanent state was approached from negative H_{SAT}. This is similar to the case of EB effect observed in FM-AFM systems [1]. In other words instead of having two easy equivalent configurations in opposite directions the top Fe layer is having a preferred easy axis parallel to the bottom hard magnetic FePt layer magnetization at the remanent state. This is due to uni-directional anisotropy, which is proved in the latter part of present work (Figure-9). The magnitude of shifting (H_B) is found to depend significantly as shown in Figure-1 on the strength of H_{SAT}. This can be explained by realizing that the bottom hard magnetic FePt layer which is coupled to top Fe layer, is still aligned parallel to H_{SAT} at remanence and therefore one need to apply more fields in opposite direction as that of H_{SAT} to switch the Fe magnetization.

The observations are similar to that of Berger et al [6, 7, 8]. However, to get more insight, the Kerr images are captured along the hysteresis loop of Figure-1. Initially the sample is saturated (here the saturation field is for the purpose of recording the minor loop of top Fe layer i.e., about -60 mT is applied as shown in Figure-1) and the background image is captured (shown in the left frame of Figure-2). Then the external field is increased in the opposite direction till the field is slightly above the coercive field. The domains are found to nucleate indicating the switching of Fe layer magnetization (the corresponding image is captured and is shown in middle frames of Figure-2). Then the external field is made zero and the domain images are captured at this state which are called as remanent images henceforth (as shown in right frames of Figure-2). One can clearly see from Figure-2 that the remanent images corresponding to higher H_{SAT} are same as that of background images i.e., Fe layer magnetization is going back to the initial starting point which is nothing but the spring effect. One can also visualize this feature in the real time as shown in Figure-3 (Multimedia view) for the case of H_{SAT} = 600 mT, which is otherwise not possible with bulk magnetization measurements. This is due to the restoration force from bottom hard FePt layer acting on the top soft Fe layer. It is to be noted that for uncoupled Fe layer the domains are found to grow with time (not shown) even when the field is released to zero as described above. This clearly indicates that the top Fe layer is more effectively pinned / coupled with bottom FePt layer for the case of higher H_{SAT} and therefore one

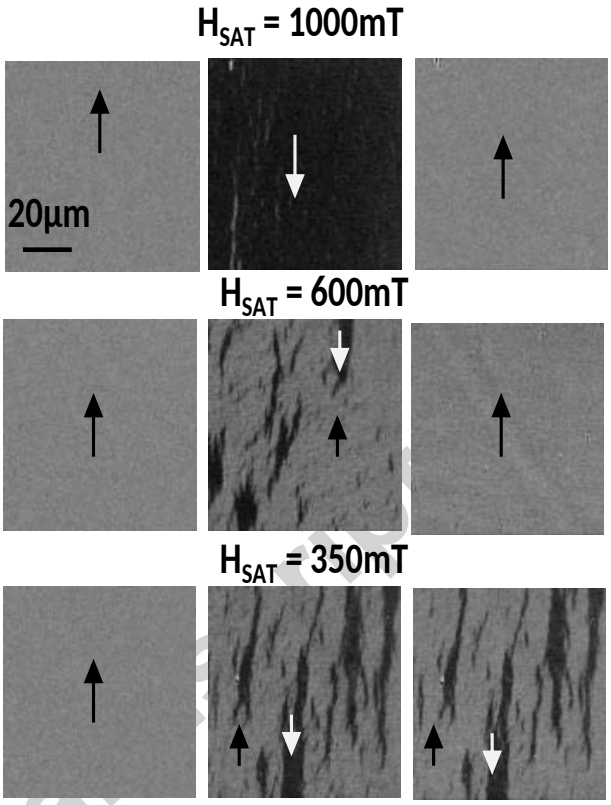


Figure 2: Kerr domain images of top Fe layer in FePt/Fe sample captured along the M-H loop of Figure-1 for different indicated H_{SAT}. (left) at saturating field i.e., background image, (middle) near the switching field and (right) at remanence condition. The arrows show the direction of magnetization. Scale bar is same for all the images.

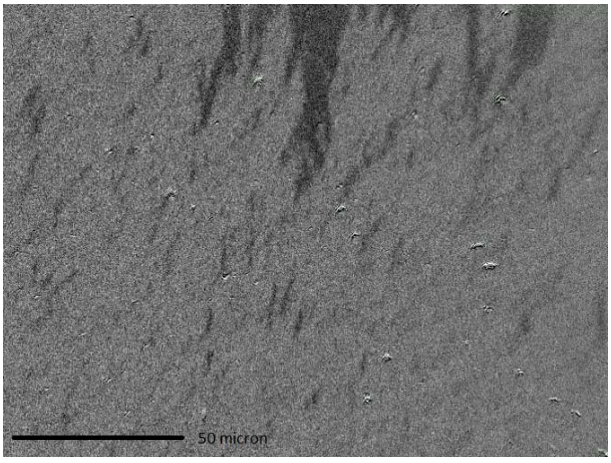


Figure 3: Real time movie showing the spring effect in FePt/Fe sample (Multimedia view).

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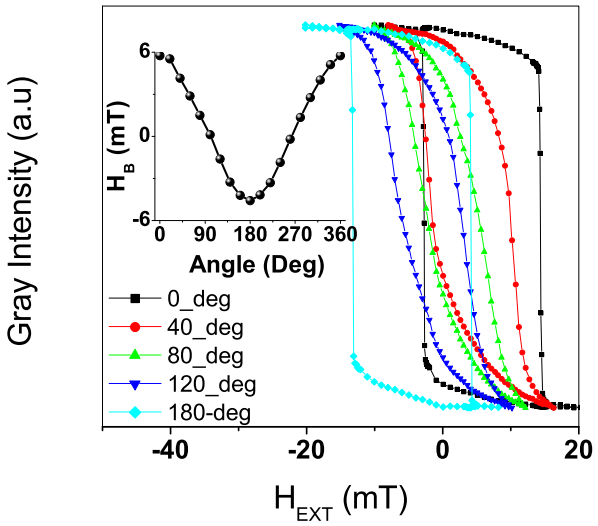


Figure 4: Longitudinal MOKE hysteresis loops of top Fe layer in FePt/Fe sample measured at remanent state approached from -330 mT (H_{SAT}) and inset show the plot of variation of biasing field (H_B) with angle between H_{SAT} and applied measuring field (H_{EXT}).

needs to apply more external field to switch Fe magnetization, explaining the increasing value of H_B with increasing H_{SAT} as shown in Figure-1.

Another relevant observation is that the coercivity (H_C) is found to depend on the strength of the H_{SAT} as shown in Figure-1. Initially the H_C is found to be almost constant, but for fields of $H_{SAT} \geq 350$ mT H_C is found to decrease accompanied by increase of H_B with increasing H_{SAT}. These results can be understood in terms of well accepted models of coupled FM-AFM layers exhibiting EB phenomena. For example, in spin-glass model the magnetic state of the interface between the FM and AFM layers is assumed to be magnetically disordered similar to that of a spin glass system. AFM layer is assumed to consist of two states viz., one part which has larger anisotropy and the second part has a weaker anisotropy [14]. Intermixing, stoichiometry deviations, roughness etc., at the interfaces are considered to be responsible for the formation of such low anisotropy region. Fraction of such low anisotropy interfacial spins can rotate almost in phase with that of FM spins and therefore are frustrated leading to enhanced coercivity. On the other hand, the more the high anisotropic AFM fraction, the more will be the shift of loop i.e., higher values of H_B and less would be the coercivity [14]. Extending this formalism to the present case, when the bottom HM FePt layer is aligned by applying a field of 1 Tesla, all the FePt spins are aligned in the applied field direction and hence can be considered that the interface disorder is low. It is to be noted that a field of about 1 Tesla is expected to saturate the studied sample as evidenced from bulk magnetization measurement [13]. Whereas, if the applied field ($H_{SAT} < 1$ Tesla) is not enough to align all the FePt spins, the interface is expected to consist of some aligned and random FePt spins i.e., in a disordered state leading to the increased H_C and decreased H_B as observed in the present work.

Further in order to study the magnetic microstructure Kerr microscopy measurements are carried out on the top soft Fe layer. The FePt/Fe bilayer was kept in remanent condition from H_{SAT} equivalent to -330 mT. This value of field is selected due to instrumental constraints so as to accommodate the high resolution objective lens and to perform angular dependent measurements. The sample was rotated in-plane i.e., the measurements were carried out as a function of angle between the applied external magnetic (H_{EXT}) field used for recording the M-H loop and H_{SAT} as shown in Figure-4. The observed azimuthal variation of H_B, as shown in the inset of Figure-4, matches with that of FM-AFM systems exhibiting exchange bias phenomena [14, 15, 16]. Further, it is to be noted that no decrease in H_B is observed when the measurements are carried out repeatedly i.e., no training effect is observed in the present work. Even when the H_{SAT} was equal to 1 Tesla no training effect was observed. It is reported in FM-AFM systems exhibiting EB phenomena if the AFM is highly anisotropic then the training effect could be absent [14]. Bottom $L1_0$ FePt layer is known to possess high magnetic anisotropy [13] and therefore could be the reason for the absence of training effect. However, some more experiments such as FePt layer with different degree of chemical ordering and hence different anisotropy, different thickness of SM and HM layers etc., are being planned to comment conclusively on this aspect.

At each angle between H_{EXT} and H_{SAT}, magnetic domains are captured along with hysteresis loops. Figure-5 shows the M-H data and magnetic microstructure i.e., domain images captured at different positions of M-H loop for the angle of 0^o and 180^o i.e., the H_{EXT} is parallel and anti-parallel to H_{SAT}. One can clearly see that the magnetization reversal is by domain nucleation and growth mechanism for both forward and backward branches of magnetization loop. However, when the Kerr microscopy measurements are carried out in transverse geometry, unlike the longitudinal case, the observed domain patterns exhibit ripple formation. The ripple is observed along both the forward and backward branches as shown in Figure-6, with the modulation being orthogonal to average magnetization [17, 18]. This

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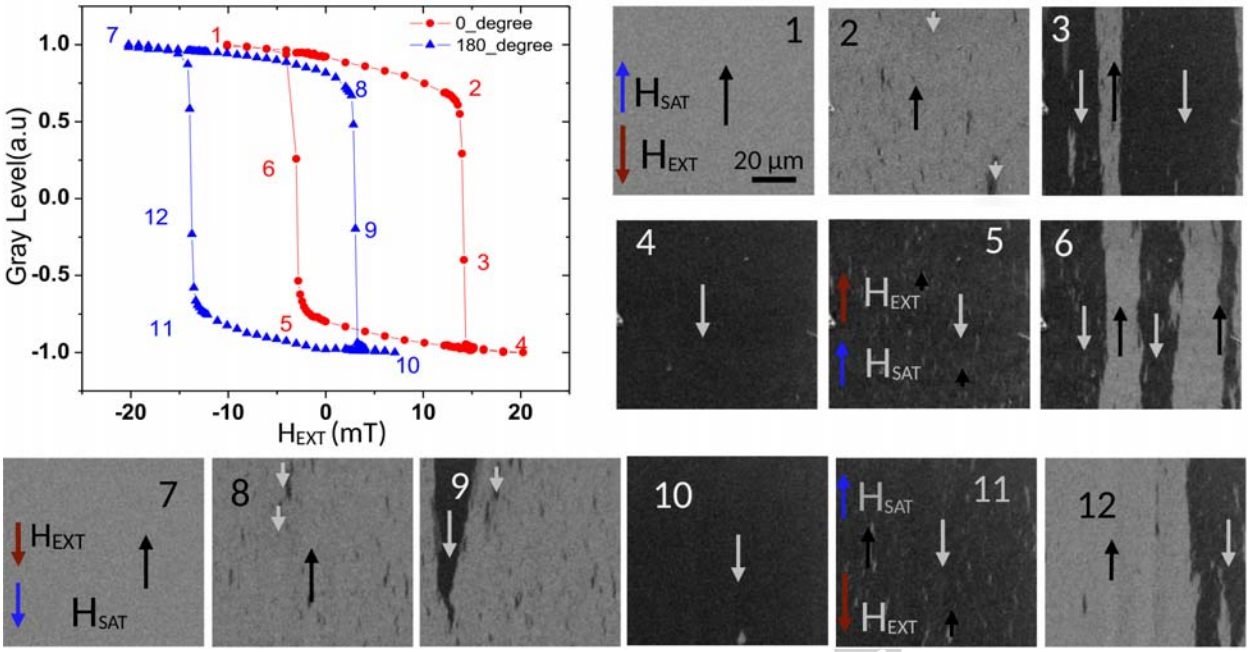


Figure 5: Longitudinal MOKE hysteresis loops of top Fe layer in FePt/Fe sample measured along and at 180^o to the H_{SAT} (-330 mT) with the corresponding domain images captured along the M-H loop at the indicated points. Scale bar is same for all the images.

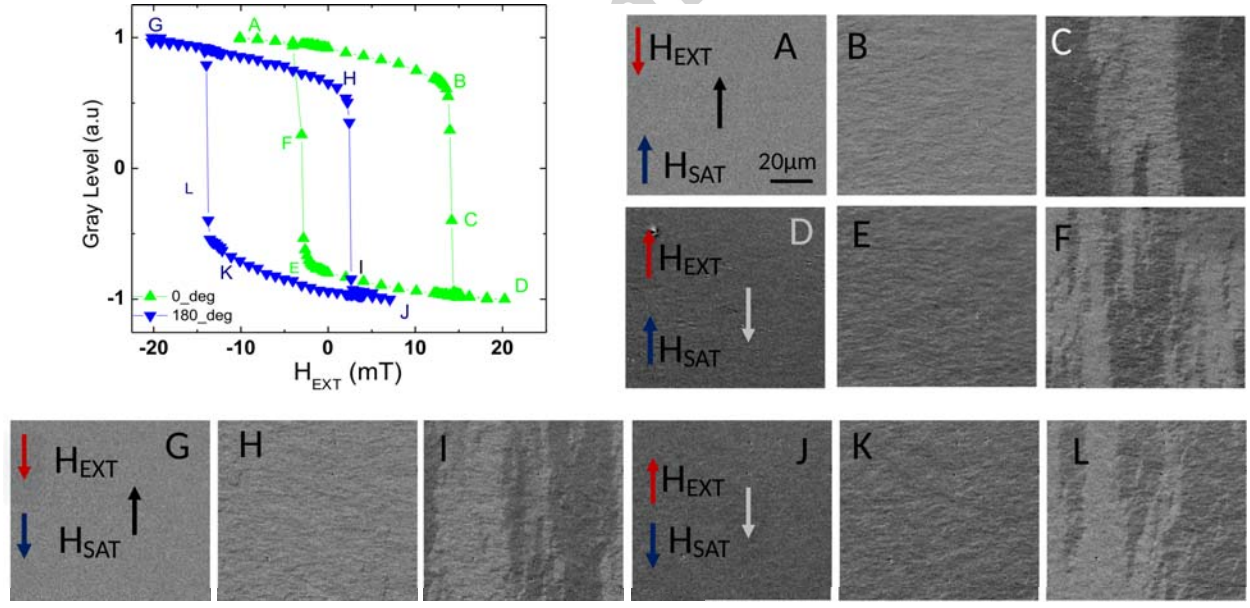


Figure 6: Transverse MOKE hysteresis loops of top Fe layer in FePt/Fe sample measured at 0^o and 180^o to the H_{SAT} (-330 mT) with the corresponding domain images captured along the M-H loop at the indicated points. The arrows show the direction of magnetization. Scale bar is same for all the images.

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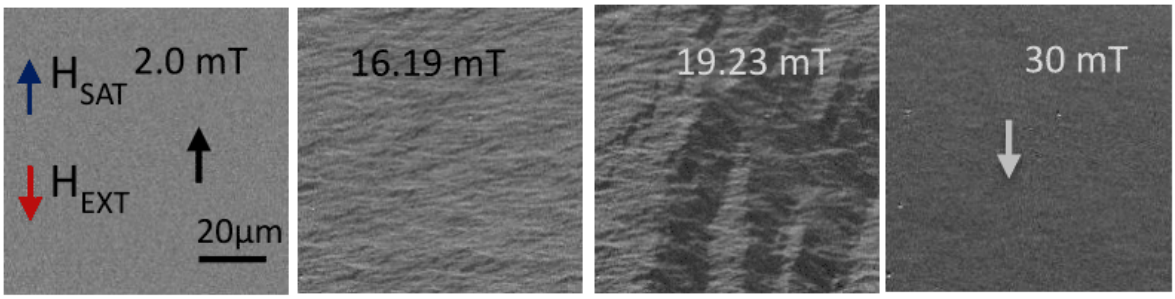


Figure 7: Transverse MOKE domain images of top Fe layer in FePt/Fe sample measured when H_{SAT}=1 Tesla. The arrows show the direction of magnetization. Scale bar is same for all the images. The images are captured during M-H loop measurement similar to that of Figure-6(A)-(D), however with H_{SAT}=1 Tesla.

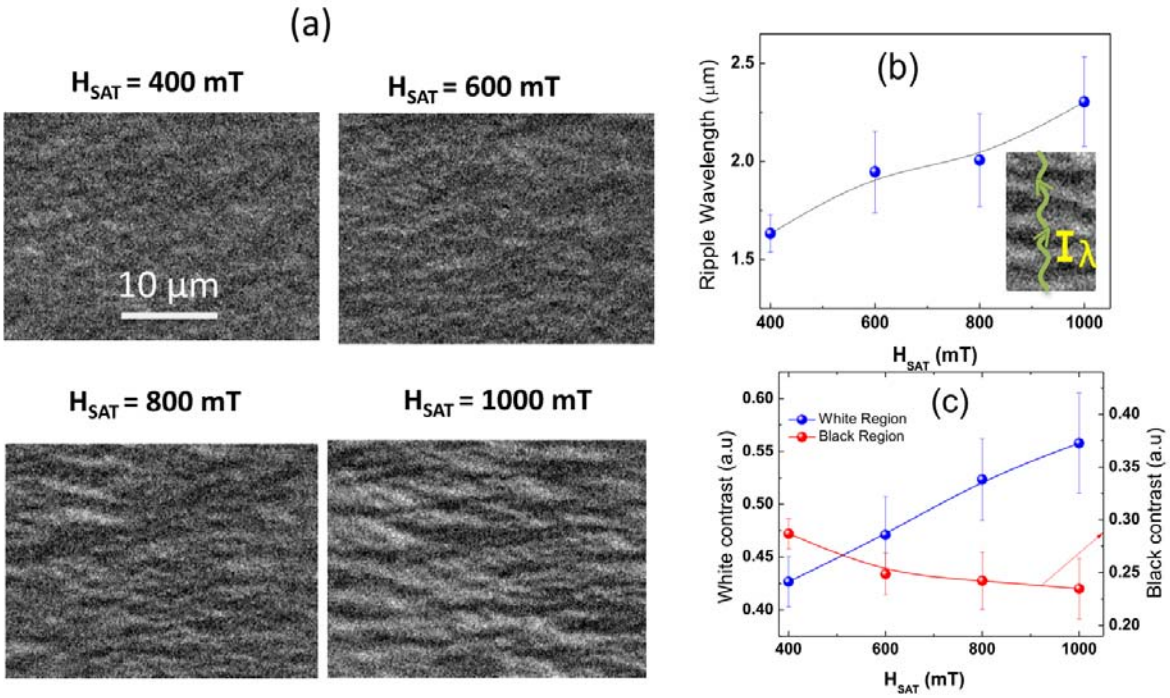


Figure 8: (a) Transverse MOKE domain images of top Fe layer in FePt/Fe sample measured at different H_{SAT}. Scale bar is same for all the images. (b) Plot of magnetization ripple wavelength with increasing H_{SAT} and insert shows the zoom image of magnetization ripple. (c) Plot of variation between magneto-optic contrast of dark and bright domains with increasing H_{SAT}. Solid line is guide to eye

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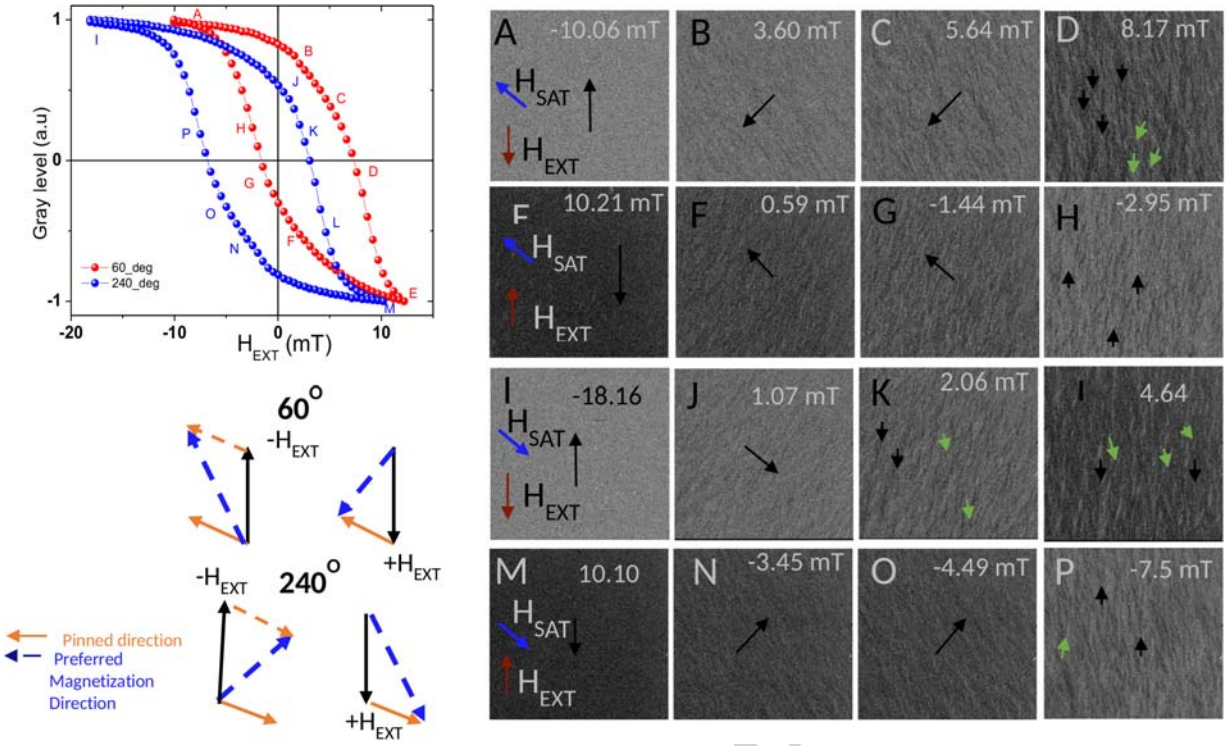


Figure 9: Longitudinal MOKE hysteresis loop and domain images captured along the M-H loop of top Fe layer in FePt/Fe sample measured at 60^o and 240^o with respect to H_{SAT}. Scale bar is same for all the images. The arrows show the direction of magnetization. Top right show the pictorial diagram showing the competition between the two forces acting viz., H_{EXT} and H_{SAT} to explain the domain evolution.

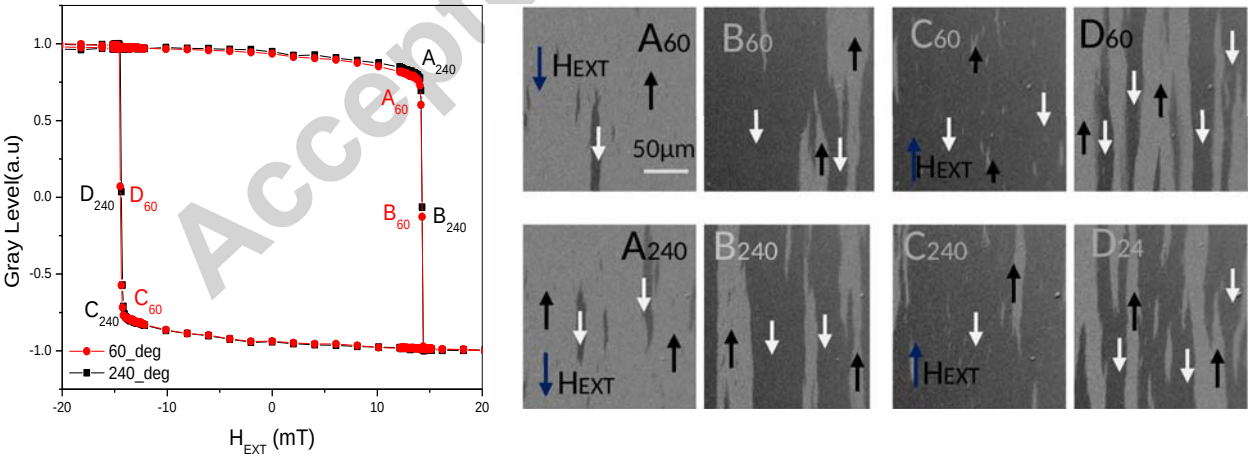


Figure 10: Longitudinal MOKE hysteresis loop and domain images captured along the M-H loop of uncoupled Fe film measured at 60^o and 240^o. Scale bar is same for all the images. The arrows show the direction of magnetization.

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is same even for the case of H_{SAT}=1 Tesla as shown in Figure-7. The observed ripple like feature could be indicative of magnetization twisting of soft magnetic layer in exchange spring magnet systems as reported by Chumakov et al., and McCord et al [19, 20]. Using Kerr microscopy, McCord et al., have reported chirality reversal for planar interface domain walls in exchange-coupled hard/soft magnetic $Tb_{45}Fe_{55}$(50 nm) /$Gd_{40}Fe_{60}$(50 nm) bilayers. It is reported that domain nucleation and lateral domain wall propagation play key role in the chirality reversal [20]. Similarly, Chumakov et al., have studied the magnetization process in $Sm_{40}Fe_{60}$ (88 nm)/$Ni_{80}Fe_{20}$ (62 nm) exchange spring films and reported the formation of 180^o domain state along the easy axis at remanent state[19]. Textured contrast i.e., magnetization ripple orthogonal to the field direction is observed along the reversible branch of hysteresis loop followed by the nucleation and growth of regular domains along irreversible branch [19]. In the present work also, one can see that initially with increasing field the observation of ripple like features (indicative of magnetization twisting of soft magnetic layer as reported by Chumakov et al.,[19]) followed by domain nucleation and growth. With further increase in H_{EXT} the domains starts to nucleate and grow whose magnetization direction is parallel to external field direction as shown in Figure-6 (C), (F), (I) and (L). It is observed that modulation pattern (not shown here) remains even after the domain nucleation and growth. Ripples disappear at sufficiently higher fields, as high as close to saturation of the loops.

It is worth to mention here that same phenomena has also been reported even in conventional exchange bias systems. The occurrence of the magnetization dispersion resulting in magnetization ripple formation in FM layer induced by exchange interaction with an AFM layer is reported by Schuller et al., in Fe/MnF_2 [21]. In the present study also it is observed that magnetization dispersion or twisting of soft Fe layer during magnetization reversal increases with the increasing H_{SAT}. This is evident from the increase in the mean wavelength of ripple and also from the contrast between bright and dark domains as shown in Figure-8. Images captured along the M-H loop in transverse geometry, similar to as that of Figure-6(E), for different H_{SAT} values are considered as shown in Figure-8(a). Using Digimizer software the average intensity of white and black regions is measured and is plotted in Figure-8(c). Both amplitude and wavelength of the ripple structure are found to increase with H_{SAT} suggesting that magnetization dispersion has been increased during magnetization reversal with increasing H_{SAT}. We consider that the twisting or dispersion of magnetization is increasing with H_{SAT} because Fe moment trace more angle as coupling increases along the interface before switching in the opposite direction. This again hints at the necessity of higher fields to switch Fe magnetization with increasing H_{SAT} and hence explaining the tuning of exchange bias with field history.

Figure-9 shows the M-H data and magnetic microstructure for the angle of 60^o and 240^o between H_{EXT} and H_{SAT}. One can see from the data that the magnetization reversal for both forward and backward branches have considerable changes in domain structure. Reversal is taking place by magnetization rotation by forming ripple pattern and the modulations are found to be reproducible. From Figure-9(A) to (C) images magnetization moments are aligned in certain direction with respect to H_{EXT}. Gradually it rotates with the application of H_{EXT} and then as shown in image Figure-9(D), the domains whose magnetization direction is in H_{EXT} direction starts growing and then gradually these ripple pattern are wiped by these domains. Same pattern is observed in images Figure-9(E) to (H) which corresponds to backward branch of magnetization loop. Therefore, for both the branches the domain evolution is same i.e, first by magnetization rotation and then by domain wall motion. The same is the case for the angle of 240^o. But the difference for both forward and backward branches at a given angle, lies in magnetization ripple direction i.e, both are opposite corresponding to initial points (Figure-9(B), (F); Figure-9(J), (N)). This can be understood by considering the competition between the two forces acting viz., H_{EXT} field which is trying to pull along its direction and other one is the pinning direction or biasing direction H_{SAT} which is now 60^o and 240^o as shown in Figure-9. The resultant direction of magnetization will be governed by this competition merely. This gives us a clear evidence that the top SM Fe layer is pinned with bottom HM FePt layer and hence explains the observed EB phenomena. Otherwise for both forward and backward branches the magnetization ripple direction should have been same. This statement is substantiated by recording the Kerr microscopy data of uncoupled Fe film of about 22 nm thickness. The observations are typical for a soft magnetic film exhibiting uniaxial anisotropy. For all the in-plane angles, the magnetization reversal is by domain nucleation and growth. Figure-10 show the hysteresis loop along with domain images measured at 60^o and 240^o deg (the angle between the easy axis and the applied field for measuring loop i.e., H_{EXT}). One can clearly see the difference in domain evolution of uncoupled and coupled Fe layer by comparing the data of Figure-9 and Figure-10. There-

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fore, the modulation pattern observed for the case of FePt/Fe layers (Figure-9) is because of uni-directional anisotropy of the SM Fe layer as a consequence of the competition of H_{SAT} and H_{EXT}.

In conclusion, Kerr microscopy study of top soft magnetic Fe layer is reported in exchange spring coupled $L1_0$ FePt(30 nm)/Fe(22nm)bilayer system. The hysteresis loops of Fe layer measured at the remanent state of the HM layer are found to be shifted along the field axis similar to the case of exchange bias effect observed in ferromagnetic-antiferromagnetic systems. It is observed that one can tune the magnitude of exchange bias shift by reaching the remanent state from different saturating fields (H_{SAT}) and also by varying the angle between measuring field and H_{SAT}. The hysteresis loops and domain images of top soft Fe layer conclusively confirms that soft magnetic layer at remanent state in such exchange coupled system is having unidirectional anisotropy.

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