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Journal

APPLIED PHYSICS LETTERS, 89(7)

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Publication Date

2006-08-17

DOI

10.1063/1.2336742

Peer reviewed

Magnetization depth dependence in exchange biased thin films

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(Received 7 March 2006; accepted 10 July 2006; published online 17 August 2006)

The depth dependence of the magnetization has been studied in antiferromagnet/ferromagnet (AF/FM) exchange coupled systems. Results from vector magnetometry and magneto-optical Kerr effect probing both the AF/FM and FM/air interfaces demonstrate the existence of a magnetization depth profile in FeF_2/FM (FM=Fe, Ni, and Py) bilayers, contrary to the assumptions of most exchange bias models. The appearance of asymmetrical hysteresis loops below the AF Néel temperature (T_N) is explained by the creation of spring-like walls parallel to the AF/FM interface and the existence of incomplete domain walls. Changes in the reversal mechanism above T_N have also been discussed.
 [DOI: 10.1063/1.2336742]

Thin film magnetic heterostructures are very important for technologies based on the manipulation of physical properties controlled by the interface region. One of the most interesting systems from both fundamental and applied points of view is the one formed by a ferromagnet (FM) and an antiferromagnet (AF) in intimate contact.[1,2] Below the Néel temperature of the antiferromagnet (T_N) the exchange coupling across the interface gives rise to a shift of the hysteresis loop along the magnetic field axis.[3] This feature is of great interest for a broad range of applications such as in spin electronics, giant magnetoresistance, sensing devices, magnetic random access memory, data storage, and in modification of activation energies in fine particles.[4–6] Besides the hysteresis loop shift the exchange bias (EB) phenomenon also exhibits an increase of coercivity,[7] training effect,[8] asymmetrical hysteresis,[9] and modified magnetization reversal mechanisms.[10]

Despite the technological impact of EB, the underlying mechanism of this phenomenon is still not fully understood, especially concerning the magnetic structure in the FM and AF layers. Several models have been put forward to explain realistic EB bias values. They fall into two main categories: one considering a spin structure through the thickness of the FM or AF layers,[11–13] and the other assuming lateral domain structures and magnetization reversal through nucleation of inverse domains and domain wall propagation.[14] Experimentally, various techniques have been used to image AF and/or FM domains: photoemission electron microscopy,[15] magneto-optical indicator film,[16] magnetic force microscopy,[17] and Kerr microscopy.[18] These techniques only provide information about the lateral magnetic domain structure. Other methods, e.g., polarized neutron reflectometry,[19] resonant soft x-ray scattering,[19,20] and Mössbauer spectroscopy,[21] have been applied to the study of domain structures parallel to the interface. However, the existence of a magnetization structure in the depth of the FM and how it influences the reversal mechanism remain unresolved.

In this letter, we unambiguously demonstrate the existence of domain walls in the FM parallel to the AF/FM interface. Magneto-optical Kerr effect is used to probe the magnetization close to the AF/FM and FM/air interfaces. These results combined with vector magnetometry measurements reveal that vertical spring-like domain walls can coexist with a lateral domain structure in the FM and can be controlled by the FM crystalline anisotropy. It is also shown that EB induces drastic changes in the reversal process.

Three sets of AF (70 nm)/FM (70 nm) bilayers were prepared by e-beam evaporation on single crystalline MgF_2 (110). The FeF_2 was grown at 300 °C and becomes an AF below the Néel temperature T_N=78 K. Three FM materials with different crystalline anisotropies, Fe, Ni, and Permalloy (Py), were deposited at 150 °C and capped with a 4 nm Al layer. X-ray diffraction shows that FeF_2 is epitaxial whereas the FM is polycrystalline.[22]

Magnetic characterization has been carried out by superconducting quantum interference device (SQUID), vector vibrating sample magnetometer (VSM), and magneto-optical Kerr effect (MOKE). Vector magnetometry measures the longitudinal and transverse components of the total magnetic moment of the sample, whereas MOKE probes only the bottom or top part of the 70 nm thick FM, since its penetration depth is about 30 nm. Both the substrate and FeF_2 are transparent in the visible spectrum; thus we can separately analyze the magnetization reversal of the FM close to either the AF/FM or FM/air interfaces by illuminating the upper or lower side of the sample, respectively. In addition, the reversibility of the magnetization has also been studied by SQUID minor hysteresis loops.

All samples exhibit a well defined uniaxial anisotropy above T_N, with the easy axis along FeF_2 [001] in the sample plane. A negative exchange bias is established by cooling across T_N in a small positive external magnetic field along this easy axis.

The sample with higher crystalline anisotropy, i.e., the FeF_2/Fe bilayer, exhibits virtually no difference in SQUID and MOKE loops measured on both FM interfaces at 10 K, revealing that the magnetic structure is not depth dependent

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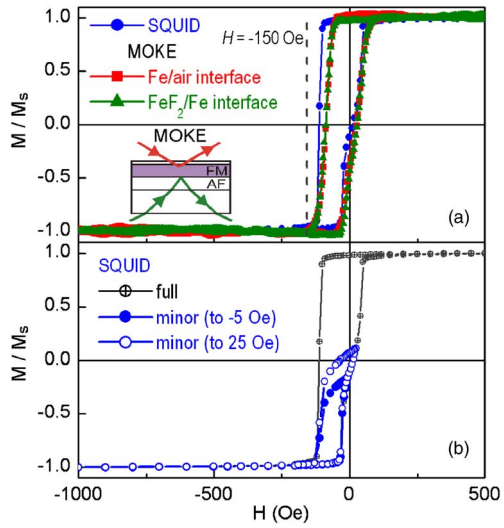

FIG. 1. (Color online) FeF_2/Fe hysteresis loops at 10 K. (a) SQUID and MOKE on both Fe interfaces. (b) Minor loops by SQUID.

[Fig. 1(a)]. The reversal from positive to negative saturation is abrupt and irreversible as shown by open minor loops [Fig. 1(b)]. This transition can be understood in terms of nucleation of inverse domains and propagation of domain walls perpendicular to the interface. An illustration of the magnetization just beyond the coercivity along the decreasing branch, at $H=-150$ Oe, is sketched in Fig. 4(a), where all Fe magnetic moments are aligned along the easy axis.

A different behavior is found in FeF_2/Ni bilayers (Fig. 2). MOKE loop from Ni/air interface is square and symmetric, similar to the FeF_2/Fe case. However, the one from the AF/Ni interface is asymmetric with an abrupt switching from positive saturation and a gradual tail extending to negative saturation [Fig. 2(a)]. SQUID hysteresis loops show a similar asymmetry and lie between the two MOKE loops. Since each MOKE loop probes about half of the total FM thickness extending from each of the two interfaces, this result constitutes a direct evidence of the existence of a magnetic depth profile in the FM. This magnetic structure extends from the AF/FM interface into the FM thickness and gives rise to the asymmetry of the loops.

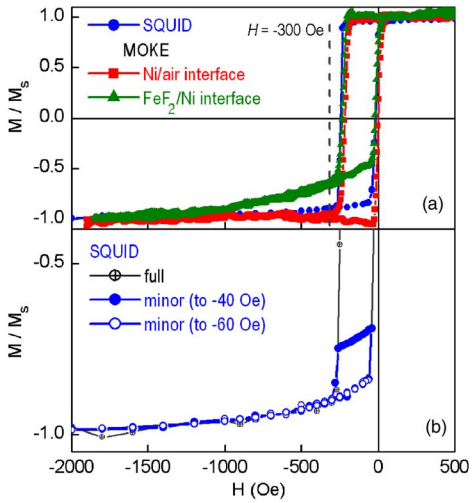

FIG. 2. (Color online) FeF_2/Ni hysteresis loops at 10 K. (a) SQUID and MOKE on both Ni interfaces. (b) Minor loops by SQUID.

Minor loops [Fig. 2(b)] show that the magnetization reversal involves two different processes. The rounded part at negative fields is reversible, while the jump around the coercive field is irreversible. Coming from positive saturation, the magnetization reversal starts at $H=-200$ Oe, likely by nucleation and propagation of domain walls perpendicular to the interface. At −300 Oe the upper part of the Ni layer (far from the AF) is fully negatively saturated, as indicated by the MOKE loop on the FM/air interface. However, the MOKE signal from the AF/FM interface shows that the FM is not yet saturated, and thus an in-depth domain structure has been created. A possible macroscopic scenario of this domain structure is a spring-like domain wall, as sketched in Fig. 4(b) where a magnetic structure extends from Ni spins antiferromagnetically coupled to the AF[22] towards the upper part of the Ni layer where all spins are inverted. Since the penetration depth of light is about 30 nm and the thickness of Ni is 70 nm, the spring domain wall should span less than 40 nm. A typical Bloch wall width in Ni is about 80 nm;[23] therefore, this spiral-like structure could be an incomplete domain wall (IDW), i.e., a non-180° wall. This is in qualitative agreement with Kiwi's model, which predicts the existence of IDW in an exchange bias system with a compensated interface.[13]

With further decrease of the magnetic field, the spring-like wall parallel to the interface narrows by an incoherent rotation of the magnetization; i.e., the whole magnetization progressively rotates, but each spin forms a different angle with the magnetic field depending on its position in depth. As the Zeeman energy overcomes the exchange energy that favors antiparallel alignment of FM interfacial moments with uncompensated AF moments, the MOKE signal slowly approaches saturation. Increasing or decreasing the magnetic fields below the coercive field shrinks or expands the wall in a reversible process as closed minor loops show [Fig. 2(b)]. The mechanism is asymmetric due to the unidirectional anisotropy of the AF. When the field increases to −40 Oe the antiferromagnetic exchange coupling between Ni and FeF_2 moments annihilates the parallel domain wall and Ni reverses by nucleation and irreversible perpendicular domain wall motion.

In contrast, in materials with low magnetocrystalline anisotropy, such as Py in FeF_2/Py bilayers, only one reversal mechanism is involved, and there are no abrupt transitions in the $M-H$ curves. The hysteresis loops from MOKE and SQUID measurements are quite different, although all show virtually no coercivity and a slow approach to negative saturation [Fig. 3(a)]. As in the Ni case, SQUID curves always fall between the MOKE loops from FM/air and AF/FM interfaces, confirming the existence of a magnetic structure through the Py layer thickness. Decreasing the field from positive saturation, the MOKE signal from the upper side of the Py layer (Py/air) is always smaller than that from the AF/Py interface, indicating that the incoherent rotation of the magnetization starts in the outmost layer of the Py thin film, and that these Py moments drag the magnetic moments underneath creating a spiral structure that extends to the AF/FM interface. For example, at $H=-140$ Oe the magnetization from spins close to the Py/air interface is zero while that from spins close to the AF/Py is still positive. At this field, a spiral-like structure [Fig. 4(c)] extends throughout the 70 nm thick Py layer, with a null magnetic moment averaged on the upper part along the field direction due to the creation of an

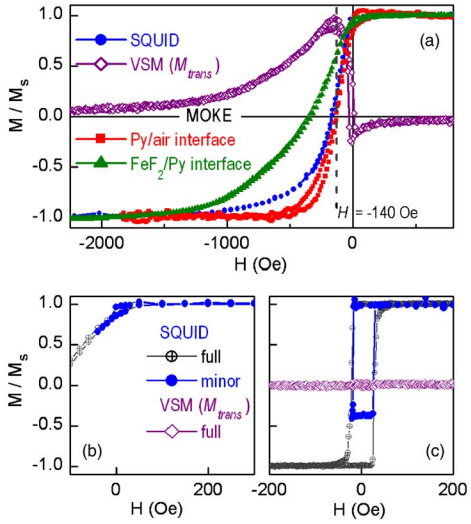

FIG. 3. (Color online) FeF_2/Py hysteresis loops. (a) SQUID, transverse VSM, and MOKE on both Py interfaces at 10 K. (b) Minor loop by SQUID at 10 K ($T<T_N$). (c) Minor loop by SQUID and full transverse VSM loops at 90 K ($T>T_N$).

IDW. The existence of an IDW in this system is also consistent with the typical domain wall width of Py being around 100 nm,[24] and is confirmed by vector VSM measurements. The VSM transverse magnetization loop [Fig. 3(a)] proves that the reversal is by rotation. The magnitude of the transverse peak, with a maximum of ~95% of the total magnetic moment of the sample, demonstrates that the maximum angle between extreme spins in the spring-like wall must be smaller than 180°, hence being an IDW. Closed minor loops [Fig. 3(b)] show that the reversal process of the IDW is fully reversible.

The minor hysteresis loops of FeF_2/Py above T_N are different from those below T_N [Fig. 3(c)]. At 90 K, the transition is abrupt and irreversible, with a finite coercivity, and the transverse component is null, typical of a magnetization reversal by nucleation and domain wall motion perpendicular to the interface, and quite different from the process below T_N, for which reversal takes place by incoherent rotation of magnetic moments parallel to the interface. This result proves that exchange bias can induce drastic changes in the magnetization reversal mechanism of a FM. All the hysteresis loops of the three sets of samples show, above T_N, no exchange bias and the square shape characteristic of uniaxial anisotropy thin films. In addition to other well known features of EB, such as loop shift, increase of coercivity, training effect, and blocking temperatures below T_N, the change in the reversal process is an important feature that must be taken into account in applications and theoretical models fitting realistic EB values.

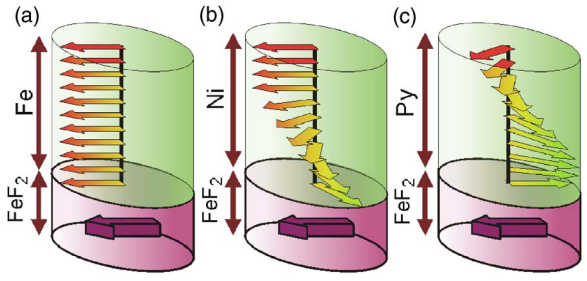

FIG. 4. (Color online) Depicted profile of the magnetization in the FM layer at 10 K for (a) FeF_2/Fe at $H=-150$ Oe, (b) FeF_2/Ni at $H=-300$ Oe and (c) FeF_2/Py at $H=-140$ Oe. (The AF/FM coupling is antiferromagnetic.)

In conclusion, we showed the existence of a depth-dependent FM magnetization in exchange biased systems. Magneto-optical measurements demonstrate the existence of a magnetic structure through the FM thickness for materials with a small crystalline anisotropy (Ni, Py) [Figs. 4(b) and 4(c)], while for higher anisotropies (Fe) this in-depth structure is absent [Fig. 4(a)]. Vector magnetometry measurements reveal the reversibility of these depth-dependent magnetic configurations. The formation of the depth-dependent structure is related to a change in the magnetization reversal mechanism below the Néel temperature of the AF and is in agreement with the existence of IDWs predicted by Kiwi's model.

Work at UCSD is supported by the U.S. Department of Energy. Financial support from European Marie Curie OIF for one of the authors (R.M.), from Alexander-von-Humboldt Foundation for one author (O.P.), and from Spanish MECD, CICYT, and Catalan DURSI for another author (X.B.) is also acknowledged. Work at UCD is supported by ACF-PRF and the Alfred P. Sloan Foundation.

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