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Exchange coupling and macroscopic domain structure in a wedged permalloy/FeMn bilayer

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Local Kerr effect and magnetometry measurements reveal that switching in exchange-coupled wedged-permalloy/FeMn bilayers involves only two macroscopic domains, extending across the entire sample, separated by a 180° domain wall, which moves along the wedge direction. The squareness of the hysteresis loop of such exchange-coupled layers depends on the thickness variation of the sample under measurement. [S0163-1829(98)50146-4]

Recently a great deal of attention has been focused on the ferromagnet/antiferromagnet (FM/AF) exchange coupling[1–5] and its applications in spin-valve giant magnetoresistance devices.[6] The hysteresis loop of a FM layer exchange coupled to an AF layer is shifted from the origin by an amount known as the exchange field (H_E), accompanied by an enhanced coercivity (H_c). The characteristics of the FM/AF exchange coupling, which is at the heart of these devices, depends sensitively on the constituent materials and their thicknesses, as well as temperature. The dependence on the thickness of the constituent layers has provided considerable insight into the elusive FM/AF coupling. For example, the $1/t_{\mathrm{FM}}$ dependence of H_E where t_{FM} is the thickness of the FM layer, demonstrates that the exchange coupling is transmitted across the FM/AF interface.[2,5] In FM/NM/AF trilayers, evidence of exchange coupling transmitted across a nonmagnetic (NM) space layer has also been observed.[7] The experimental observation of the $1/t_{\mathrm{FM}}^{3/2}$ behavior of H_c at low temperatures has confirmed the theoretical predictions that are based on the random-field interactions at the FM/AF interface.[8]

The magnetic domains of both FM and AF layers play a prominent role in FM/AF exchange coupling. Most theoretical models of exchange coupling have explicitly featured the FM and the AF domains.[9–11] Although direct evidences of AF domains in exchange-coupled systems remain scarce, the observed dependence of exchange coupling on t_{AF}, the AF layer thickness, is likely to be a manifestation of the AF domains.[12] On the other hand, the FM domains and the movement of domain walls can be directly imaged by Kerr microscopy and magnetic force microscopy, and indirectly inferred by hysteresis loops. In exchange-coupled FM/AF bilayers with a uniform FM layer, during switching, the FM layer breaks up into many domains with complex wall motions.[13] Questions have also been raised concerning the validity of hysteresis loop measurement as a means for measuring the intrinsic characteristics of the exchange coupling.[14]

In this paper, we report on the results of magneto-optic Kerr effect (MOKE) and vibrating sample magnetometry (VSM) measurements on a *Py*/FeMn bilayer, where the FM *Py* (permalloy=$Ni_{81}Fe_{19}$) layer is wedged and the AF FeMn ($Fe_{50}Mn_{50}$) layer is uniform. We used MOKE and VSM to map out the FM domains and their switching behavior. The FM domain structure in an exchange-coupled wedged FM layer is greatly simplified. During switching, there are only two large FM domains, extending across the entire sample, separated by a 180° wall, which moves along the wedge direction. Consequently, the MOKE and VSM measurements taken from corresponding locations on the specimen give the same results. The observation of these large domains and their switching behavior allows the establishment of a direct relationship between the magnetic domains and the hysteresis loop results. These results also show that these domain structures are unique to exchange coupling with a wedged FM layer.

The FM/AF exchange coupling has been most commonly measured via magnetometry, e.g., VSM. To study the thickness dependence of a particular constituent material, many samples with different thicknesses need to be separately measured using either individually made specimens, or samples cut from a large specimen with a wedge-shaped constituent layer. MOKE, with the advantages of a small sampling area (defined by the size of the laser beam), high sensitivity, and fast measurement offers another means of measuring exchange-coupled systems. Surprisingly, few MOKE studies of exchange coupling have been reported. Notably, Mauri *et al.* have studied a *Py*/FeMn bilayer by *in situ* MOKE, where the thickness of the *Py* layer was systematically reduced by ion milling after each MOKE measurement, thus revealing the FM thickness dependence of the exchange coupling.[5]

The use of specimens that contain a wedged constituent layer offers much advantage in studying the thickness dependence. Such specimens alleviate the run-to-run variation commonly encountered in individually fabricated samples. MOKE measurements can be directed at different locations on the specimen without dicing the specimen into many smaller pieces, as would be the case for VSM measurements. However, the constituent layers in a large specimen, wedged or otherwise, are physically connected. Since the hysteresis loop measured by MOKE at one region may be influenced by the presence of the contiguous layers, the MOKE results measured from various locations of a large specimen may be different from the VSM results taken from many smaller and isolated samples. Indeed, it is the evolution of the domain structure that ultimately dictates the relationship between the results measured by MOKE and VSM.

Specimens of *Py*(wedge)/FeMn/Cu were deposited using alloyed targets of *Py* ($Ni_{81}Fe_{19}$) and FeMn ($Fe_{50}Mn_{50}$) onto Si substrates in a computer-controlled multisource deposition

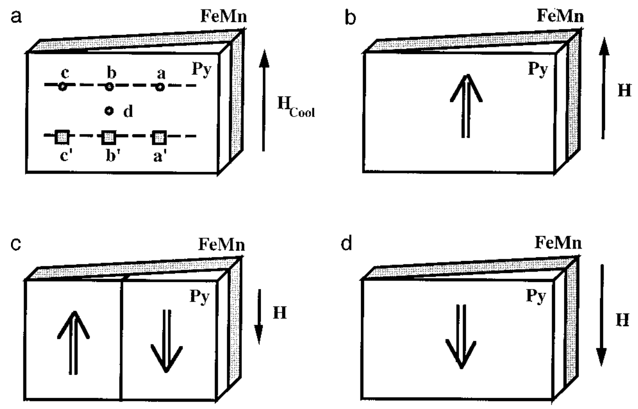

FIG. 1. (a) Schematic descriptions of the exchange-coupled *Py* (wedge)/FeMn(300 Å) specimen, 5 cm×2 cm in size, with a wedged *Py* layer (40–300 Å) from left to right. The deposition field, cooling field ($H_{\rm cool}$), and measuring field are perpendicular to the wedge direction. MOKE measurements are taken at various spots along the line marked *a, b, c*. The VSM measurements are taken from individual samples cut along the line marked a', b', c'. (b) In the field range of $H \geqslant -40$ Oe, the entire sample has one domain with up magnetization. (c) In the intermediate field range, there are two domains with opposite magnetization, separated by a 180° wall. (d) In the field range of $H \leqslant -250$ Oe, the entire sample has one domain with down magnetization.

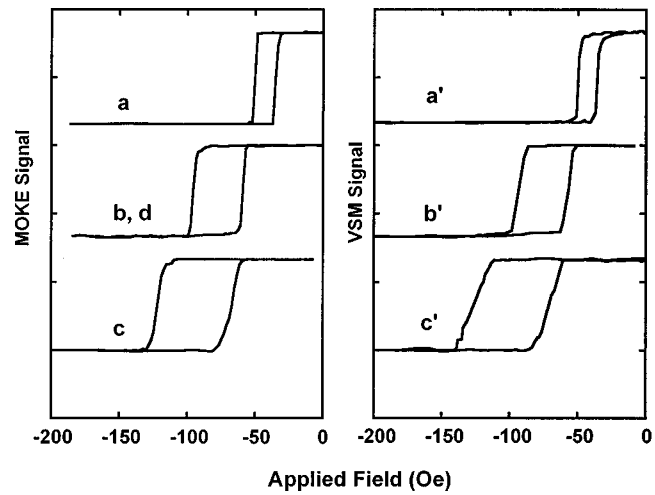

FIG. 2. Representative hysteresis loops measured by MOKE (left) and VSM (right), where *a, b, c, d* and a', b', c' refer to the locations on the specimen described in Fig. 1(a).

system with a base pressure of 5×10^{-8} torr. The Cu underlayer was used to promote the growth of AF fcc FeMn. While the FeMn (300 Å) and Cu (300 Å) layers were uniform, the *Py* layer was a wedge from 40 to 300 Å across a distance of 5 cm. Each location on the specimen along the wedge direction therefore corresponds to a specific *Py* thickness. During deposition, a magnetic field of about 200 Oe was applied in plane and perpendicular to the wedge direction. After deposition, the sample was heated to above ($T_N \approx 440$ K) of FeMn and cooled to room temperature in a magnetic field of 10 kOe, also applied in plane and perpendicular to the wedge direction. This established an unambiguous exchange coupling with an unidirectional anisotropy perpendicular to the wedge direction. The sample geometry and the field directions are shown in Fig. 1(a).

The large specimen (about 5 cm×2 cm) with a wedged *Py* layer was cut into two halves along the wedge direction for the MOKE and the VSM measurements. During MOKE and VSM measurements, the magnetic field was applied in the same direction as those of the deposition field and cooling field. In the MOKE measurements, the laser beam (about 1 mm in size) was directed at various spots of the large specimen along the wedge direction [*a, b, c*, in Fig. 1(a)]. The magnetic field was supplied by a pair of Helmholtz coils with a field range of −300 Oe to 300 Oe. For the VSM measurements, the strip was cut into many small pieces (about 3 mm×3 mm in size) along the wedge direction. The small samples [their locations marked as a', b', c' in Fig. 1(a)] were individually measured by VSM. In short, as shown in Fig. 1(a), the MOKE and VSM measurements were taken along two parallel wedge directions separated by 1 cm.

Representative MOKE results at locations *a, b, c*, and the VSM results at the corresponding locations a', b', and c' are shown in Fig. 2. In all cases, the hysteresis loops measured by MOKE and VSM at the same location along the wedge direction give the same values of H_E and H_c. Furthermore, the MOKE measurement at point *d* gives the same results as that at point *b*, which is at the same location along the wedge, but laterally different. These results establish that the scanning MOKE measurements on an uncut wedged specimen give the same results as those obtained from VSM using many separate samples at corresponding locations.

From the hysteresis loops one obtains exchange field (H_E) and coercivity (H_c) as a function of *Py* thickness. The MOKE and VSM results are shown in Fig. 3, plotted as $1/t_{\rm FM}$, where $t_{\rm FM}$ is the thickness of the *Py* layer, to highlight that both H_E and H_c exhibit the $1/t_{\rm FM}$ dependence. The results from MOKE and VSM are in excellent agreement. The exchange-coupling energy per unit area is $H_E\, t_{\rm FM}\, M_{\rm FM}$, for which we obtain the value of 0.057 erg/cm^2, using $M_{\rm FM} = 780$ emu/cm^3 for *Py*. It is of interest to note from the extrapolation that H_E is small but finite for $1/t_{\rm FM}\rightarrow 0$, whereas

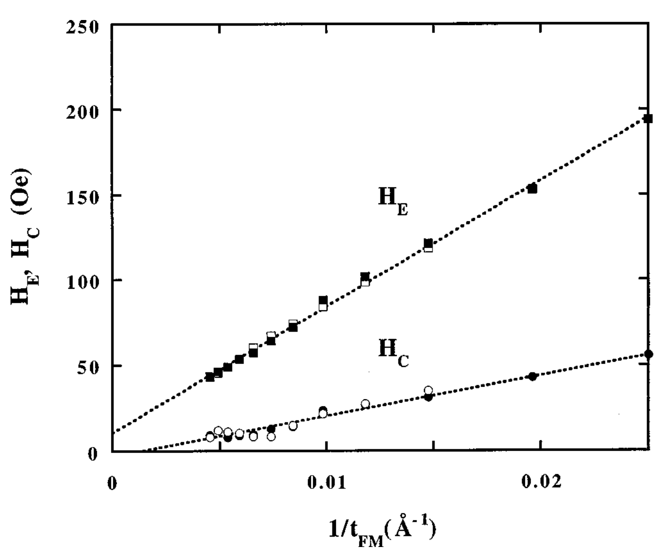

FIG. 3. Exchange field H_E (squares) and coercivity H_c (circles) of *Py*(wedged)/FeMn(300 Å) measured by VSM (open symbols) and MOKE (solid symbols) as a function of $1/t_{\rm FM}$, where $t_{\rm FM}$ is the *Py* thickness.

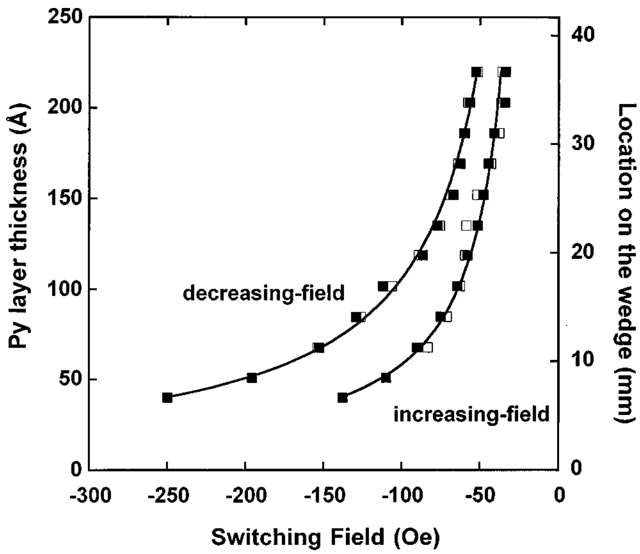

FIG. 4. The switching field measured from VSM (open symbols) and MOKE (solid symbols) for increasing-field branch and decreasing-field branch as a function of *Py* thickness and location on the wedged *Py* layer.

H_c becomes zero at a finite $1/t_{FM}$ manifesting that the $1/t_{FM}$ dependence of H_E and H_c is applicable only for FM layers with reasonably small t_{FM}.

As mentioned earlier, there is no *a priori* reason to expect the MOKE results measured from an uncut wedge sample along one wedge direction to be the same as the VSM results measured from the corresponding samples along a different but parallel wedge direction. The two sets of measurements yield the same results because the exchange-coupled wedged layer has a specific domain structure. From a hysteresis loop, the states with $+M$ and $-M$ are two single-domain states with magnetization pointing in the $+H$ and $-H$ directions, respectively. At the switching field, the magnetization switches from one single-domain state to another. In the present case, local measurements using MOKE and VSM allow us to map out the actual domain structure and the domain wall movement in a large specimen.

The switching fields (at which $M=0$) for the increasing-field branch (from $-M$ to $+M$) and the decreasing-field branch (from $+M$ to $-M$) are shown in Fig. 4 as a function of the *Py* thickness and the location on the wedged specimen. Consider the decreasing-field branch for example. For $H \geqslant -40$ Oe, the entire specimen has all the moments pointing up as shown in Fig. 1(b). At a slightly more negative field, the magnetization at the thick end of the *Py* layer begins to switch to the opposite direction. For example, at $H = -90$ Oe, the moments to the right of point *b* are pointing down, while the moments to the left of point *b* remain pointing up, i.e., there is a 180° domain wall at point *b* when $H = -90$ Oe. The 180° wall moves further to the left of point *b* at a more negative field until $H \leqslant -250$ Oe, at which point the entire specimen has the magnetization pointing down. Thus, we have conclusively demonstrated that the transition from one single-domain state to another is accomplished by the growth of one single domain at the expense of the other. The magnetization directions of the two domains are along the unidirectional direction established by field cooling. The formation of only two domains separated by a 180° wall, which is perpendicular to the wedged direction [Fig. 1(c)], is precisely the reason that VSM and MOKE give the same results. It may be noted that in uniform FM layers during switching, there are numerous domains which are often small (on the μm scale) and complex, requiring magnetic microscopy for observation.[15] In contrast, by employing a wedged FM layer, a simple two-domain structure is obtained.

The switching field varies monotonically, but not linearly, with the thickness of the *Py* layer, as shown in Fig. 4. Thus, the rate of wall movement due to the external magnetic field (i.e., dx/dH) is not constant. For a given increment of field, the rate of the 180° wall movement is smaller for the thinner *Py* layers. This is because the exchange field is inversely proportional to the *Py* thickness and location on the wedge.

Because of the unique domain structure in the present case, a hysteresis loop is in fact a signature of the movement of the 180° wall sweeping across the sample under measurement. More specifically, the width (ΔH) of the switching from $+M$ to $-M$, or the squareness of the loop, is dH/dx times the sample dimension in the wedged direction. Consequently, we have the unusual situation that the width ΔH of switching depends on the *Py* layer thickness (through the value of dH/dx) and is proportional to the sample *size*. Indeed, as shown in Fig. 2, the values of ΔH for both MOKE and VSM are narrower for thicker *Py* layers. Furthermore, for a specific *Py* thickness, ΔH for MOKE is narrower than that of VSM, because of the smaller sampling area in MOKE measurements. This indicates that for μm-size *Py* layers, as in field sensing devices, ΔH would be even smaller, ultimately only limited by the 180° domain-wall width.

In FM/AF bilayers with a uniform FM layer, switching between the $\pm M$ states occurs within a narrow ΔH range, in which the entire FM layer breaks into many domains including closure domains. Both the stabilization and the imaging of the domain structure have proven to be challenging.[13] In the present case, by taking advantage of the thickness dependence of the switching field, the wedged FM layer impedes the progression into many domains throughout the FM layer. Instead, there is one single 180° domain wall moving across the sample. Furthermore, the location of the 180° wall can be dictated by the external magnetic field. This domain structure, the simplest achieved to date, can be used to study domain-wall dynamics in exchange-coupled FM/AF bilayers.

In summary, MOKE and VSM measurements on wedged Py/FeMn bilayers show that switching in the exchange-coupled systems involves only two macroscopic domains separated by a 180° wall. Under the external field, the domain wall sweeps along the wedge direction. MOKE and VSM give the same results precisely because of the unique domain structure. We also show that the squareness of the hysteresis loop in this case is sample size dependent. The greatly simplified domain structure can be used as a model system for studying domain dynamics in exchange-coupled systems.

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