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Co layer thickness dependence of exchange biasing for IrMn/Co and FeMn/Co

K. A. Seu[a] and H. Huang
Department of Physics, College of William and Mary, Williamsburg, Virginia 23187

J. F. Lesoine
Department of Physics, Moravian College, Bethlehem, Pennsylvania 18018

H. D. Showman
Department of Physics, College of William and Mary, Williamsburg, Virginia 23187

W. F. Egelhoff, Jr. and L. Gan
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

A. C. Reilly[b]
Department of Physics, College of William and Mary, Williamsburg, Virginia 23187

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We present a high resolution study of the ferromagnetic layer thickness dependence of exchange bias field (H_{EB}) and coercivity (H_C) in IrMn/Co and FeMn/Co bilayers using the magneto-optical Kerr effect. Samples are sputtered wedges on silicon with Co thicknesses ranging from 1 to 17 nm. The IrMn/Co (with exchange bias interface energy of ~0.14 erg/cm^2) shows square loops, a smooth increase in H_{EB} with inverse thickness, and a complicated behavior for coercivity, perhaps due to competition with thickness dependent coercive mechanisms. The FeMn/Co (with exchange bias interface energy of ~0.059 erg/cm^2) shows more rounded loops, a plateau of H_{EB} with decreasing thickness, and a smooth increase in coercivity with inverse thickness. [DOI: 10.1063/1.1555332]

Exchange biasing still remains an intensively studied but incompletely resolved phenomenon.[1,2] It is generally agreed that the phenomenon is due to interfacial interaction between a ferromagnet (FM) and antiferromagnet (AF) in a bilayer film. Several models have been proposed, assuming different spin orientations and varying effects of interface roughness and domain formation in the FM and AF layers. Recent experiments have shown the complicated nature of exchange biasing and how different models may be applicable to different material systems.

Exchange-biased Co systems provide an interesting study of this interaction. Unlike systems such as Fe/MnF$_2$ where the nature of the antiferromagnetism is well known and thus allows it to serve as a model system,[3] or NiFe systems whose behavior has been well studied, Co presents more complications. For example, polycrystalline Co grown on a face centered cubic (fcc) buffer shows increasing amounts of hexagonally close packed (hcp) stacking faults with increased thickness.[4] The domain structure and coercivity of Co is also very thickness dependent.[5] Giant magnetoresistance studies on FeMn/Co exchange-biased spin valves have indicated that the exchange biasing may be altered at higher thicknesses.[6] X-ray magnetic circular dichroism and x-ray magnetic linear dichroism studies of FeMn/Co have shown that the spin flop coupling model may not apply to this system.[7] Further work has shown that Co may induce ferromagnetic ordering at the FM/AF interface, as seen in NiO/Co bilayers.[8] Anisotropic magnetoresistance measurements have shown a thickness dependent exchange bias interface energy in CoO/Co and may also indicate a twist in the magnetization of the Co.[9]

We present a study of exchange biasing and coercivity of FeMn/Co and IrMn/Co on Co layer thickness, where the Co is a wedge from 1 to 17 nm. Such a study on these two systems has not been reported. We study these two systems as examples of different exchange bias interfacial strengths. The magneto-optical Kerr effect (MOKE) was used, which gives us excellent resolution of the effect versus FM layer thickness.

The samples used were grown by dc magnetron sputtering on a Si (100)/thermal-oxide substrate. The base pressure was 5×10^{-10} Torr and the background Ar pressure was 2 mTorr. A Ta/Cu buffer layer was used to promote fcc AF film growth. The first sample incorporated an IrMn AF with a Co FM wedge: Ta (1 nm)/Cu (5 nm)/IrMn (10 nm)/Co (1–17 nm)/Al$_2$O$_3$ (1.2 nm). The second sample is similar to the first sample, except it uses FeMn as the AF: Ta (1 nm)/Cu (5 nm)/FeMn (10 nm)/Co (1–17 nm)/Al$_2$O$_3$ (1.2 nm). The choice of 10 nm for the AF layer thickness is large enough so the blocking temperature is greater than 150 °C.[10,11] Additionally, two nonwedge, FeMn/Co films were used to check against the wedge: Ta (1 nm)/Cu (5 nm)/FeMn (10 nm)/Co (X nm)/Al$_2$O$_3$ (1.2 nm), where $X=3.10$. In all of the samples, Al$_2$O$_3$ is formed from sputtered Al exposed to air and is used as a capping layer to prevent oxidation. X-ray photoelectron spectroscopy shows no evidence of the forma-

[a]Author to whom correspondence should be addressed; electronic mail: keoki@camelot.physics.wm.edu
[b]Electronic mail: reilly@physics.wm.edu

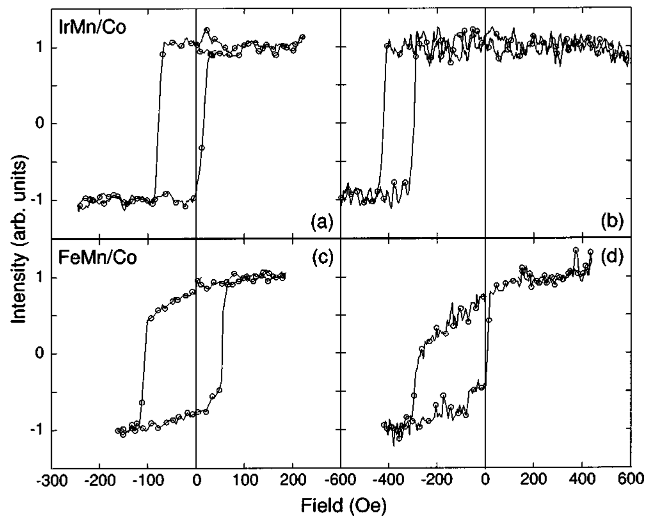

FIG. 1. Example MOKE curves from the data collected. The upper set are from IrMn/Co with Co thicknesses of: (a) 17 nm (thick end) and (b) 4.2 nm (thin end). The lower set are from FeMn/Co, with Co thicknesses of (c) 16.4 nm (thick end) and (d) 4.6 nm (thin end). A vertical line indicates zero field.

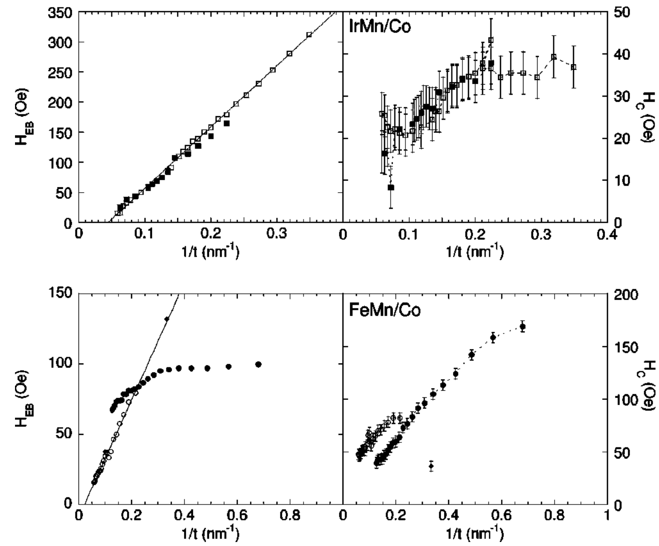

FIG. 2. Plots of the exchange bias H_{EB} and coercivity H_C for IrMn/Co (top) and FeMn/Co (bottom) vs inverse Co thickness. For each plot, two sets of data are shown, a data set initially taken (empty circles/squares), and a data set taken at a later time (filled). The lines in the exchange bias graphs (left) are linear fits to the initial data. The dotted lines in the coercivity plots (right) are point to point guides. The two single film thickness measurements for FeMn/Co are given by diamonds. Error bars are drawn on all the graphs.

tion of oxidized CoO. Pinning was achieved by heating the samples to 250 °C and cooling in an external magnetic field of 100 Oe. The samples were pinned along the axis perpendicular to the thickness gradient.

MOKE is a powerful tool for studying magnetic materials since it has monolayer sensitivity and allows for selective probing of small regions on the surface of the sample. MOKE for metallic films has a depth resolution of ~20 nm (determined by the absorption depth) and has been shown to give the same values for exchange bias and coercivity as vibrating sample magnetometry in wedge samples.[12] The MOKE setup used is a typical longitudinal MOKE setup with two linear polarizers. A diode laser (632 nm) was modulated by a function generator at 100 kHz, and the linearly polarized beam was focused on the sample, with a beam diameter of 1 mm. The samples were placed in an electromagnet on a vertical micrometer mount with the pinning axis perpendicular to the field. This gives a 4 Å resolution in the thickness of the FM. The reflected beam is sent through a polarizer at near extinction (~1°) with the first and focused onto a photodiode, whose signal is read with a lock-in amplifier referencing 100 kHz.

Figure 1 shows various MOKE curves from the data taken. The data for the upper plots are from IrMn/Co with Co thickness at (a) 17 nm and (b) 4.2 nm. The lower plots are from FeMn/Co, where the Co is (c) 16.4 nm and (d) 4.6 nm. Since MOKE cannot measure the absolute magnetization, all the curves are centered about the origin and normalized to unity.

Figure 2 shows a plot of the exchange bias (H_{EB}) and coercivity (H_C) for IrMn/Co (upper, in squares) and FeMn/Co (lower, in circles) versus inverse Co thickness. The exchange bias plot of the IrMn/Co follows a smooth $1/t$ curve over the whole thickness range measured (shown as a linear fit). The IrMn/Co data shows very little run-to-run variation (two separate runs are shown). The FeMn/Co exchange bias also shows linear behavior over the data set range, however there is a strong run-to-run variation in H_{EB} and H_C for FeMn/Co (two separate data runs are shown in the figure). H_{EB} and H_C for the two single thickness FeMn/Co films are shown in Fig. 2 (diamonds).

H_{EB} for FeMn/Co appears to level off at smaller Co thickness (<5 nm), possibly due to a discontinuity in the Co layer.[11] Surprisingly, the coercivity for FeMn/Co continues to increase in this thickness range. For the IrMn/Co, the coercivity has a general increase with a leveling off for Co thickness <4 nm.

The whole IrMn/Co curve and FeMn/Co for thicknesses >3 nm can be well fit by a $1/t$ curve if a nonzero y intercept crossing is assumed (which means that the exchange bias will go to zero at $t=22$ nm for IrMn/Co and $t=46$ nm for FeMn/Co). The curves can also be fit with deviations from $1/t$ such as $1/t^n$, with $n\approx 1.33$. This ensures that the exchange bias goes to zero at large thicknesses. We do not have enough data to determine which is the correct fit. Thicker Co regions are needed, but MOKE again only has a probe depth of 20 nm, and it must be assumed when using thicker layers that the magnetization is uniform throughout the Co layer.

From the data it appears that the IrMn/Co sample shows strong exchange biasing as evidenced by square loops, a $1/t$ dependence of H_{EB}, and independence of data run to run. For the FeMn/Co, H_{EB} shows a linear dependence on $1/t$ for Co thickness greater than ~5 nm with a strong run-to-run data variation. This could indicate that the pinning is not strong or there is a modification in the AF layer as the Co layer is flipped.

Based on past work we expect that the FeMn thickness used is large enough for adequate pinning. There may be a dependence on the type or thickness of the buffer layer, a topic we are currently exploring.[13] Surprisingly, even though the behavior of H_{EB} shows leveling off, H_C for FeMn/Co

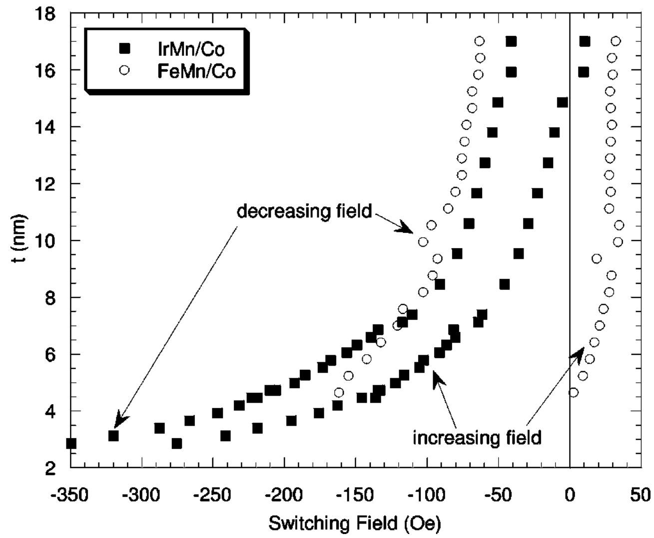

FIG. 3. Plots of the Co thickness vs switching field (where $M=0$) for IrMn/Co (squares) and FeMn/Co (circles). Arrows point to the decreasing ($+M$ to $-M$) and increasing ($-M$ to $+M$) field. There is a vertical line to indicate the zero field point.

shows a strong, smooth increase across all thicknesses.

Although the $1/t$ fit causes a nonzero field crossing, it is possible that the $1/t$ dependence for exchange bias breaks down at sufficiently large FM thicknesses.[12] Another possibility mentioned earlier is a $1/t^n$ fit, where $n \neq 1$. The theory by Stiles and McMichael support this by using small corrections (of order $1/t^2$) to $1/t$.[14–16]

Figure 3 shows the thickness of the Co wedge versus the switching field (the field where the magnetization is zero) for IrMn/Co (squares) and FeMn/Co (circles). The arrows indicate the decreasing field (from $+M$ to $-M$), and increasing field (from $-M$ to $+M$). These plots indicate simplified domain structure in the wedges, similar to the effect seen in NiFe/FeMn bilayers (where motion of a single domain wall was seen).[12,17] At an applied field of 0 Oe, all the spins are oriented in the same direction. As the field is decreased, the spins start to flip in the opposite direction. At -50 Oe, Co thicknesses on the wedge larger than 8 nm are spin flipped 180°. As the field increases to -275 Oe, all of the spins flip accordingly.

Even though the Co thickness studied is in a range of expected deviations in Co structure, the only effect we see is a small bump in H_{EB} and H_C around 7 nm for IrMn/Co, and 10 nm for FeMn/Co (most obvious in Fig. 3). This may be related to an increased in hcp stacking faults in the Co towards thick end.[4] There also appears to be a discrepancy in the coercivity of FeMn/Co and IrMn/Co at the same Co thickness. This bump showed up in all the data runs on the IrMn/Co and FeMn/Co samples.

In summary, we have presented a systematic study of the exchange bias and coercivity as a function of the Co layer thickness in FeMn/Co and IrMn/Co using MOKE. H_{EB} for the IrMn/Co is proportional to $1/t$ over the range examined, although H_C does not show a strong, smooth increase. The FeMn/Co shows linear dependence of H_{EB} on $1/t$ for Co thicknesses >5 nm with strong run-to-run variations in measurement. H_C increases smoothly over this range. The connection between coercivity and exchange bias appears to be complicated in these Co systems.

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