Dependence of exchange bias field and coercivity on spacer layer thickness in FeMn/NiFe/Cu/NiFe spin valve structures

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Magnetization reversal mechanisms in sputter deposited Cu(5)/NiFe(7)/CoFe(0.3)/ Cu(t)/CoFe(0.3)/NiFe(6)/Fe(20)/ Cu(2) spin valve systems on silicon substrates for different values of *t* in between 2.0 and 3.0 nm have been studied using vibration sample magnetometry (VSM) and magneto optic Kerr effect spectrometry (MOKE) in surface (longitudinal) and transverse geometries. The exchange bias field matches in magnitude in both the experiments and shows an oscillatory behaviour of interlayer coupling with alternative ferromagnetic and antiferromagnetic alignments, while displaying the highest H_{ex} value for Cu thickness of 2.2 nm in the investigated thickness range. The coercivity also follows an oscillatory trend with enhanced values for successive Cu thicknesses. However, the coercivity values obtained by MOKE are found to be larger compared to VSM, which is attributed to the presence of highly polarized CoFe protective layer in either side of the Cu spacer. The variations in exchange bias fields are discussed in terms of the confinement of quantum well states at the two interfaces of the Cu spacer layer.

1. Introduction

Exchange bias has attracted much attention recently both from academic and technological fronts due to the complexity involved in understanding the phenomenon as well as its technological importance for applications of magnetoresistance based sensors [1]. After the discovery of giant magnetoresistance in magnetic multilayers [2], many efforts were made by several workers to understand the exchange coupling phenomenon [3]. It was reported that the observed oscillatory nature of magnetoresistance between the adjacent ferromagnetic layers when the thickness of the nonmagnetic spacer varies originates from the periodical switching of magnetic alignments from parallel to antiparallel and vice versa [4]. Many attempts were made to explain the oscillatory nature of exchange coupling theoretically by various models [5]. However, in order to make these multilayer structures feasible for sensing geometries, one of the ferromagnetic (F) layers should be made magnetically hard by using an antiferromagnetic (AF) layer so that the magnetization reversal of the free layer can be obtained even for small fringe fields, and the pinned (hard) layer will change its state only when it is subjected to a large enough field. As a result of this pinning, there exists an exchange coupling field at the F/AF interface and this may well extend to the free ferromagnetic layer through the nonmagnetic spacer in decreasing proportion. In this paper, we report exchange coupling field and coercivity in spin valve structures as a function of nonmagnetic spacer layer thickness using vibrating sample magnetometry (VSM) and magneto optic Kerr effect (MOKE) spectrometry.

2. Experimental Details

Multilayer spin valve structures based on the configuration Cu(5)/NiFe(7)/CoFe(0.3)/Cu(t)/CoFe(0.3)/ NiFe(6)/FeMn(20)/Cu(2) were deposited by RF magnetron sputtering on Si (100) substrates for different values of *t* in between 2.0 and 3.0 nm. During sputtering, the base pressure was kept less than 10^{-7} Torr and the working Ar pressure was of 3×10^{-3} Torr. The deposition rates were about 0.21-0.25 Å/sec for all the layers. A static magnetic field of 60 Oe was applied in the film plane during the deposition of the magnetic layers to set the ferromagnetic unidirectional anisotropy axis. The thin layers of CoFe were preferred for deposition on either side of the Cu spacer layer because of their ability to prevent interdiffusion into permalloy layers due to high polarization ratio. The bottom Cu seed layer ensures good buffer and develops necessary <111> crystalline orientation. The top thin Cu layer was used for capping as it prevents oxidation of FeMn.

M-H curve profiles on all the samples were obtained using VSM and MOKE techniques. In the surface MOKE configuration, the applied field was parallel to the sample surface in the deposition field direction and also to the

632.8 nm incident laser light. Whereas in the transverse MOKE, the magnetic field was applied along the sample axis and normal to the plane of incident light and induced magnetic field direction. Transverse MOKE curves were obtained at room temperature by automatic equipment measured in the field range from 0 to 200 Oe at different wavelengths from 300-750 nm using a zenon light source The depths of MOKE reflections in both the experiments have been estimated based on the calibration experiment for penetration depths [6].

a)

3. Results and discussion

Hysteresis loops of spin valve structures for various thicknesses of Cu layer using VSM and surface MOKE are shown in figs. 1a & 1b, respectively. It can be seen that each of the curves displayed two hysteresis loops concerning the free and pinned ferromagnetic layers. The height of the loops in VSM measurements match very well in relation to their corresponding thicknesses, while the slight discrepancy in the magnitude of the reflected intensities corresponding the free and pinned layers in the MOKE loops may be due to the presence of highly polarized protective CoFe layers in either side of the Cu spacer layer. In each figure, the top part of the hysteresis with negligible exchange bias field (a few Oe equal to that of interlayer coupling field only) in both VSM and MOKE curves is related to the free NiFe layer while the swollen bottom parts of the hysteresis with sizeable exchange coupling fields and enhanced coercivities in both the VSM and MOKE curves are attributed to the top pinned layer.

The negligible magnetic anisotropy of the free NiFe layer is a characteristic of the small value of coercivity for that layer in each of the figures. However, enhanced coercivity is shown for each of the pinned layer due to the effect of exchange coupling at the F/AF interface. Interestingly, the resulting exchange bias field and corecivity from both the VSM and MOKE experiments for any given Cu thickness are comparable to each other. This needs a particular mention in the wake of the fact that the VSM curve is a characteristic of bulk magnetization, whereas the MOKE curve, which is supposed to be a surface characterizing tool and for which the reflections are estimated to be obtained from the free ferromagnetic layer as the incident wavelength is 632.8 nm, also exhibits exchange bias field of the top pinned ferromagnetic layer. This implies that the magneto optic signal carries information not only from the plane of its reflection but also from the additional planes along its trajectory. Perhaps, the data related to the top pinned layer may have come from Faraday (volume) effect [7,8] and that of the bottom free layer from Kerr (surface) effect.
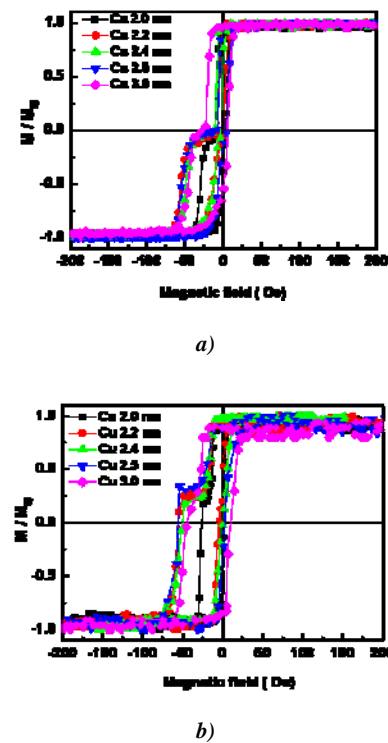

b)

Fig. 1 *Hysteresis loops of spin valve structures characterized by vibrating sample magnetometry and surface MOKE with the incident wavelength of 632.8 nm as a function of Cu spacer layer thickness*

Fig. 2 shows the variations of exchange bias field and corecivity deduced from VSM and surface MOKE loops as a function of Cu spacer layer thickness. The exchange bias field observed in both the experiments remains similar while recording the highest field for Cu spacer layer thickness of 2.2 nm in each case in the investigated range. Further, it shows an oscillatory behaviour with an approximate period of the studied range (i.e, 1 nm), as shown in fig. 2a. Many groups reported the interlayer oscillatory nature of the coupling with periodicities of the same order [9,10]. The peaks in the curves may be attributed to the ferromagnetic coupling while the troughs could be representing antiferromagnetic coupling [11]. The magnitude of the coercivity, as shown in fig. 2b, is observed to be different for MOKE and VSM measurements. Except for the 2 nm Cu thickness, the coercivity is more in MOKE measurements for all the Cu thicknesses investigated compared to the VSM data. This behaviour may be due to the presence of highly polarized and high anisotropy CoFe layer which reflects in the reflected intensity of MOKE signal. Though the coercivity appears to follow the oscillatory trend similar to that of the exchange coupling field, a close examination of the curves reveals that the enhanced coercivities are resulted for increasing Cu thickness. It implies that the thicker Cu spacer makes the spin rotations harder irrespective of whether the coupling is of ferromagnetic or antiferromagnetic.
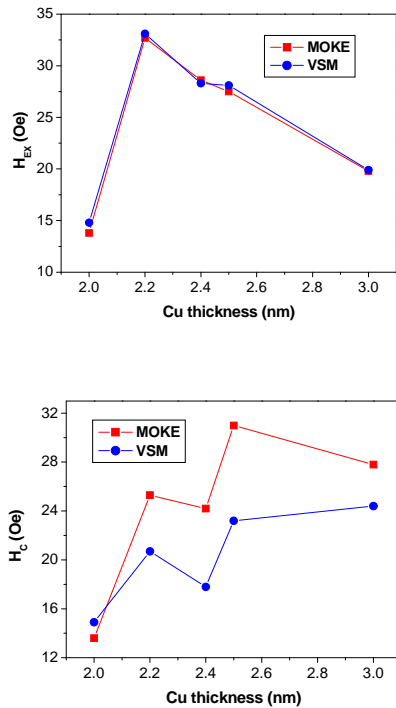
Fig. 2   Variations of a) exchange bias field, and b) coercivity of the spin valve structure deduced from the measurements of VSM and surface MOKE (with the incident wavelength of 632.8 nm) as a function of Cu spacer layer thickness

Oscillatory nature of the exchange coupling in F/Cu/F/AF structures with thin Cu layer arises due to the energy that the spacer material takes to fill the electron states up to the Fermi level at its two interfaces. The spin dependent reflections of Bloch waves at the two interfaces makes the confinement of quantum interference states in the spacer to be different for these two different interface alignment configurations. As a result, the corresponding energies, which oscillate with the spacer thickness, are also different. Thus, the difference of these oscillatory energies makes the oscillatory interlayer exchange interaction [11]. In the present study, as the thickness of the Cu spacer layer is changed, the quantum well states move either up or down in the energy depending on the details of the spacer layer band structure. The strength of the oscillatory interlayer exchange coupling is determined by the energy changes associated with filling and emptying these states as they cross the Fermi energy due to changes in thickness variations of the spacer layer. The stronger the spin dependent reflections, the stronger is the confinement and also stronger is the oscillatory coupling [12]. For the Cu spacer layer thickness of 2.2 nm, the quantum well states confinement appears stronger as evident from the large value of exchange coupling field (fig. 2a). As the Cu thickness increases further, the confinement becomes weaker resulting in smaller

exchange coupling fields. Perhaps, it could be inferred from the H_{ex} trend that the alignment of the interface quantum states may be repeated for the thickness range beyond the present study to obtain a 1 nm period oscillatory nature.
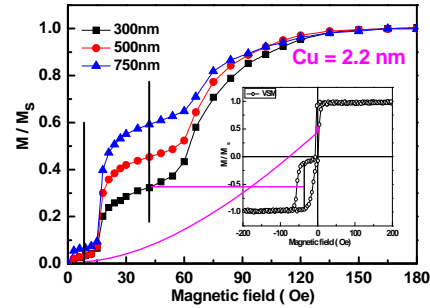

Fig. 3. Hysteresis loops of the spin valve structure when probed under AC (transverse Kerr effect) and DC (VSM) magnetic fields. The AC field measurements were made at three different wavelengths (□ - 300 nm, ○ - 500 nm and Δ - 750 nm).

Fig.3 shows the field dependence of normalized magnetization curves for the sample, Cu(5)/NiFe(7)/CoFe(0.3)/Cu(2.2)/CoFe(0.3)/NiFe(6)/FeMn(20)/Cu(2), using transverse MOKE at different wavelengths. The corresponding DC magnetic hysteresis loop taken by VSM is shown in the inset of the figure. The exchange bias field and corecivity estimated from the DC magnetic loop are equal to 33 Oe and 22 Oe, respectively. The observed AC field dependences of TKE at different wavelengths for both the free and pinned F layers have, however, been found to be quite striking. Since the TKE intensity is proportional to the magnetic moment of the layer at a given depth, the observed TKE signals can be understood as due to the magnetization rotations with the field. Consequently, the magnetization rotation is found to be soft for longer wavelengths (750 nm) at low fields, i.e. < 33 Oe (less than exchange bias field), compared to the shorter wavelengths (300 nm). And, this behaviour of soft rotation appears similar for both free and pinned layers as well. It should be mentioned here that the 750 nm longer wavelength gets Kerr reflections from a depth of 32.5 nm in the free NiFe layer apart from transmitted bulk Faraday intensities from the pinned NiFe layer. Thus the magnetic rotational contributions for this wavelength are a mix from both Faraday and Kerr effects. Thus, the magnitude of the signal at low fields appears larger. However, for the other two wavelengths of incident light (300 nm and 500 nm), the Kerr reflections are to be obtained from the depths of 28.5nm in the Cu layer close to the CoFe-Cu interface, and 29.9 nm, which is also in the Cu layer close to the Cu-NiFe interface, respectively. That means, most of the signal for these wavelengths may have come from transmitted Faraday volume effect only rather than Kerr effect based on surface reflections due to the nonmagnetic

nature of Cu layer. Further, since there is a scope for diffusion of NiFe into Cu at NiFe-Cu interface the corresponding M/Ms for 500 nm showed moderate value, while the M/Ms value for 300 nm recorded a minimum for the CoFe-Cu interface as there is little scope for diffusion of CoFe layer into the Cu layer. The rather low spin rotational contributions even for 750 nm wavelength of incident laser light in the TKE curves in fig. 3 resulting from transverse Kerr effect for the free NiFe layer further confirm the Cu diffusion at the Cu-NiFe interface.

4. Conclusions

Sputter deposited conventional spin valve structures Cu(5)/NiFe(7)/CoFe(0.3)/Cu(t)/CoFe(0.3)/NiFe(6)/ FeMn(20)/Cu(2) as a function of Cu spacer layer thickness in the range from 2-3 nm have been studied using vibrating sample magnetometry (VSM) and surface magneto optic Kerr effect (MOKE) spectrometry, and for Cu thickness of 2.2 nm by transverse MOKE geometry.

The evaluated exchange bias field and coercivity values from the hysteresis loops for these samples indicate that the Hex is larger for Cu thickness of 2.2 nm, and the exchange bias field and corecivity follow an oscillatory behaviour with Cu thickness variation. Larger coercivity values were obtained by MOKE compared to VSM, which is attributed to the high polarization level of CoFe layers.

Transverse MOKE signals at shorter wavelengths indicate that the major part of the output intensity has resulted from the Faraday volume contributions rather than the Kerr surface contributions.From the observed interlayer oscillatory coupling with alternative ferromagnetic and antiferromagnetic alignments, the results were explained as due to the confinement of quantum well states at the two interfaces of the Cu spacer layer.

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