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GMR of Co/Cu Multilayers with Reduced Hysteresis and Low-Field Response

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magnetron guns are mounted 180° apart at the bottom of a large vacuum chamber. Two Si substrates are attached to two spinner assemblies on a circular platter which is suspended 1.5" above the targets. The individual layer thickness can be precisely adjusted to within 0.5 Å by computer controlled platter rotation over the targets and is calibrated by x-ray reflectivity measurement. The film uniformity across the diameter of the Si wafer is better than 1 %. X-ray diffraction measurements were performed to characterize the structure of the Co/Cu MLs using Cu-K_α radiation. The current in plane magnetoresistance of the MLs was measured at room temperature in the transverse field geometry using an *ac* four-point technique. A vibrating sample magnetometer was used to collect the magnetization data for the MLs.

III. RESULTS AND DISCUSSION

High angle x-ray diffraction measurements on Si/[Co$t^{(1)}_{Co}$Å/Cu20Å/Co$t^{(2)}_{Co}$Å/Cu20Å$]_{15}$ indicate that these MLs are polycrystalline. The majority of the grains have a (111) texture, but there is a small fraction of the grains with a (002) orientation. Low angle x-ray reflectivity measurements show up to 5th order superlattice reflections within a 2θ range of 6° indicating a well defined periodic layered structure.

The GMR response of Si/[Co$t^{(1)}_{Co}$Å/Cu20Å/Co$t^{(2)}_{Co}$Å/Cu20Å$]_{15}$ were measured as a function of $t^{(1)}_{Co}$ and $t^{(2)}_{Co}$. Typical MR vs. H data for $t^{(2)}_{Co}$ = 3, 3.5, 4, 6 Å are shown in Fig. 1(a). The magnetoresistive hysteresis is reduced with decreasing $t^{(2)}_{Co}$, which is more clearly illustrated in MR minor loops, shown in Fig. 1(b), with the magnetic field being swept only at positive values. The hysteresis has disappeared when $t^{(2)}_{Co} < 4.5$ Å. As $t^{(2)}_{Co}$ is reduced to 3 Å, the MR value decreases drastically and the response becomes much broader. Experiments to correlate the GMR response with the ML microstructure as determined from high resolution cross-sectional TEM measurement are in progress. For $t^{(2)}_{Co} < 4.5$ Å, the magnetization reversal process of the MLs proceeds as follows. As the applied field is reduced, the magnetization of the thin Co layers switches while the magnetization of the thick Co layers remains coupled to the field direction. This is evident in the magnetization loop for $t^{(2)}_{Co}$=4 Å shown in Fig. 1(c). With this reversal, the GMR response quickly rises to its maximum. As the applied field becomes negative, the magnetization of the thick Co layers switches irreversibly near -50 Oe setting the coercivity in the magnetization loop. Meanwhile, the magnetization of the thin Co layers switches back toward the positive field direction, maintaining the GMR response near its maximum. The GMR response decreases as the magnetization of the thin Co layers aligns with that of the thick Co layers in the applied field direction.

The reduced hysteresis is the result of a combination of two

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***Abstract*--We present the results of a systematic study on optimization of the giant magnetoresistance (GMR) response in Co/Cu multilayers (MLs) for Cu layer thickness near the second oscillatory peak. Co/Cu MLs with alternating thick ($t^{(1)}_{Co}$) and thin ($t^{(2)}_{Co}$) Co layers have been prepared in the form of [Co$t^{(1)}_{Co}$Å/Cu20Å/ Co$t^{(2)}_{Co}$Å/Cu20Å]$_{15}$. We have found that the magnetoresistive hysteresis of these MLs is reduced with decreasing $t^{(2)}_{Co}$ and has disappeard when $t^{(2)}_{Co}$ < 4.5 Å. We have obtained an optimal GMR response with a field sensitivity of 0.13%/Oe over a field region of ~60 Oe centered at ~50 Oe. This architecture may enable the use of Cu/Co MLs in low-field magnetic sensor applications.**

I. Introduction

The Co/Cu MLs at the second oscillatory peak (t_{Cu}=20 Å) show GMR values of ~33% with a H_S~400 Oe [1] and are promising for magnetic field sensor applications. Significant magnetoresistive hysteresis, however, impedes their application. Efforts have been made to improve the performance of Co/Cu MLs [2, 3]. The magnetoresistive hysteresis has been reduced when Co/Cu MLs were prepared in the form of alternating thick and thin Co layers with Cu layer thickness fixed at the second oscillatory peak [2]. Taking advantage of our planetary magnetron deposition system, which is fully programmable for depositions from simple to complicated ML structures and capable of very precise control of film thickness and uniformity [4], we have carried out a systematic study of the reduction of magnetoresistive hysteresis for Co/Cu MLs near the second oscillatory peak. The performance of these MLs has been optimized to demonstrate the feasibility of application for Co/Cu MLs as low-field magnetic sensors.

II. Experimental Methods

Co/Cu MLs with alternating thick and thin Co layers, [Co$t^{(1)}_{Co}$Å/Cu20Å/Co$t^{(2)}_{Co}$Å/Cu20]$_{15}$ ($t^{(1)}_{Co}$=12-60 Å, $t^{(2)}_{Co}$ =2.5-15 Å), were deposited on 4" (100) Si wafers using a four-source *dc* magnetron sputtering system [4]. The deposition pressure was 1.25 mTorr and the base pressure was typically 6×10^{-7} Torr. Two 5"x10" rectangular Co and Cu

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effects: the relatively stronger coupling of the magnetization in the thick Co layers to the applied magnetic field, and the relatively larger effect of the interlayer antiferromagnetic (AF) exchange coupling on the thin Co layers. Since the interlayer

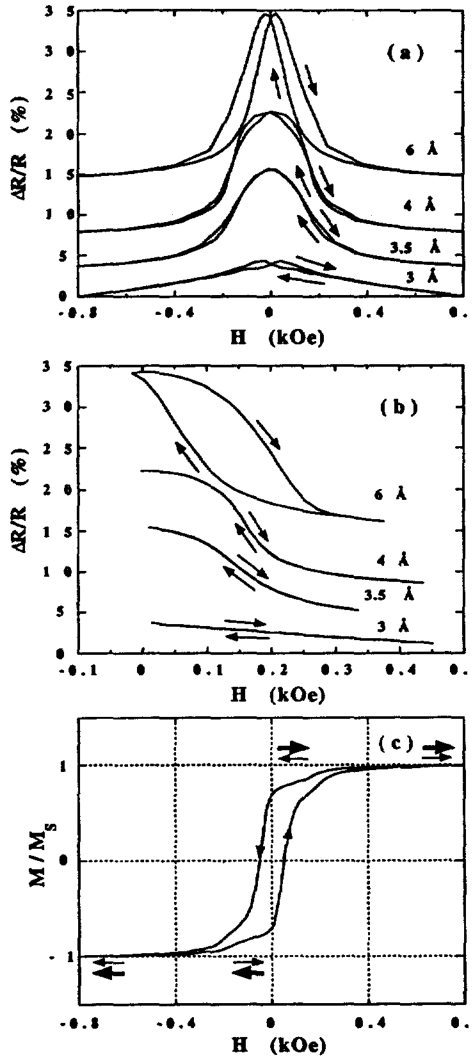

Fig. 1: (a) Typical GMR response and (b) corresponding minor loop for Si/[Co30Å/Cu20Å/Co$t^{(2)}_{Co}$Å/Cu20Å]$_{15}$/Cu20Å with $t^{(2)}_{Co}$ =3, 3.5, 4, 6 Å. (c) Typical magnetization loop for $t^{(2)}_{Co}$ =4 Å. For clarity, the curves in (a) and (b) have been translated. The thick and thin arrows in (c) represent the magnetization directions in the thick and thin Co layers.

exchange coupling does not depend strongly on the Co layer thickness, the energy in the interlayer exhange coupling becomes larger relative to the energy due to crystalline anisotropy or other sources of hysteresis as the Co layer becomes thinner. As a result, the magnetization of the thinner Co layer responds anhysteretically to the competing applied magnetic field and interlayer AF exchange coupling.

The minor loops are anhysteretic since only the magnetization of the thin layer switches in response to the interlayer AF coupling. In fact, the minor loop remains anhysteretic for negative values of the sweep field as long as it is more positive than the field required for reversal of the thick Co layer magnetization.

It is clear from Fig. 1(a) that the hysteresis reduction occurs at the expense of broadening of the GMR response. The saturation magnetic field, measured as the Full Width at Half Maximum, ΔH_{FWHM}, of the response increases with decreasing $t^{(2)}_{Co}$ below 6 Å and the field sensitivity ($\Delta R/R/\Delta H_{FWHM}$) drops from 0.11%/Oe at $t^{(2)}_{Co}$=6 Å dramatically to about 0.05%/Oe at t^{2}_{Co}=4 Å. Based on the observation that the measured GMR response is governed by the two factors, i.e. the coupling of the thick Co layer magnetization to the applied field and the interlayer AF exchange coupling, we have taken two further approaches to optimize the performance of these Co/Cu MLs.

The first method was to increase the thickness of the thick Co layers so that their coupling to the applied magnetic field can be enhanced. A thicker Co layer switches at a lower applied field. This is evident from Fig. 2 by the rapid decrease of the coercivity with increasing thick Co layer thickness,

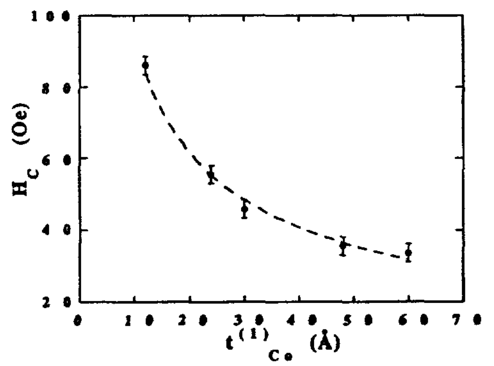

Fig. 2: The coercivity of Si/[Cot$^{(1)}_{Co}$Å/Cu20Å/Co4Å/ Cu20Å]$_{15}$/Cu20Å, measured from the magnetization loops, as a function of $t^{(1)}_{Co}$. The dashed line is a guide to eye.

$t^{(1)}_{Co}$, from 12 to 60 Å. The GMR response becomes narrower with increasing $t^{(1)}_{Co}$, as clearly demonstrated in Fig. 3. It with increasing $t^{(1)}_{Co}$. The field sensitivity is improved and is increased from 0.04%/Oe to 0.07%/Oe with a GMR value of 13% and, most importantly, the center of the linear regime of the response or the bias point is shifted to a lower field value from ~250 Oe to ~50 Oe.

Since the magnetization of the thin Co layers switches in response to the interlayer AF coupling, a narrower GMR response can be achieved if the AF coupling strength can be moderately reduced. Our second approach was therefore to increase the Cu spacer thickness, t_{Cu}, to above that for the second GMR oscillatory peak (20 Å) while keeping the thicknesses of the two Co layers, $t^{(1)}_{Co}$ and $t^{(2)}_{Co}$, fixed at 30 Å and 4 Å, respectively. The results are shown in Fig. 4. Although the response becomes hysteretic as a whole with increasing t_{Cu}, the minor loop response remains anhysteretic (Fig. 4(b)), consistent with reversible switching of the magnetization of the thin Co layers at positive field values.

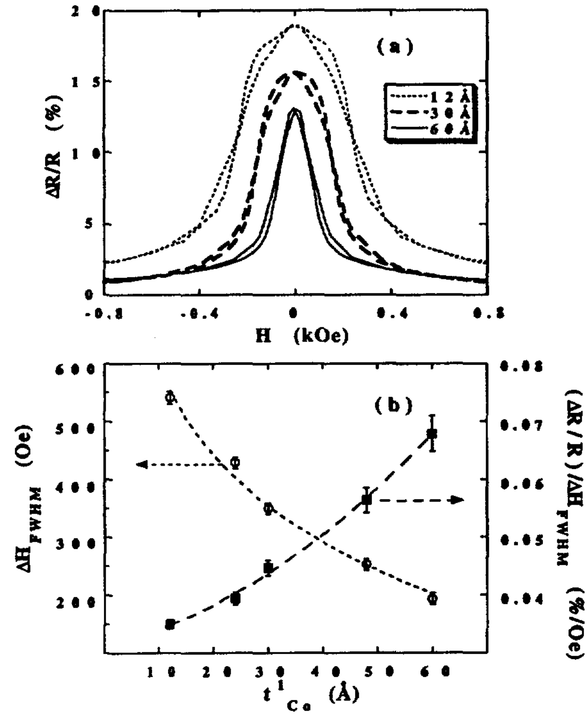

Fig. 3: (a) Typical GMR response and (b) corresponding Full Width at Half Maxmum, ΔH_{FWHM}, and field sensitivity, $(\Delta R/R)/\Delta H_{FWHM}$, of the response for Si/[Cot$^{(1)}_{Co}$Å/Cu20Å/Co4Å/Cu20Å]$_{15}$/Cu20Å with $t^{(1)}_{Co}$ varying from 12 to 60 Å. The dashed line in (b) is a guide to eye.

The response becomes narrowed with increasing t_{Cu}. It is evident from the minor loop response that the bias point is shifted to a lower field value and the field sensitivity, $\partial(\Delta R/R)/\partial H$, for the linear regime of the response is maximized at 0.13%/Oe with a GMR value of 16% for t_{Cu}=21.5 Å over a field region of ~60 Oe centered at ~50 Oe.

IV. Conclusions

In conclusion, in the region of the second oscillatory peak of the Co/Cu MLs, we have successfully obtained optimal GMR response by engineering ML structures with alternating thick and thin Co layers. GMR response of these MLs exhibits reduced magnetoresistive hysteresis with decreasing thin Co layer thickness ($t^{(2)}_{Co}$). In particular, the minor loop measurements indicate that the magnetoresistive hysteresis has completely vanished at $t^{(2)}_{Co}$ <4.5 Å. At present, we do not know if a continuous Co layer can be formed for a thickness below 6Å. We are in the process of examining the ML microstructure using high resolution cross-sectional TEM. Enhancing the coupling of the thick Co layer magnetization to the applied magnetic field while moderately reducing the interlayer AF coupling strength has improved the performance of these MLs, resulting in a low saturation magnetic field and an enhanced field sensitivity. This may enable application of Co/Cu MLs as low-field sensors.

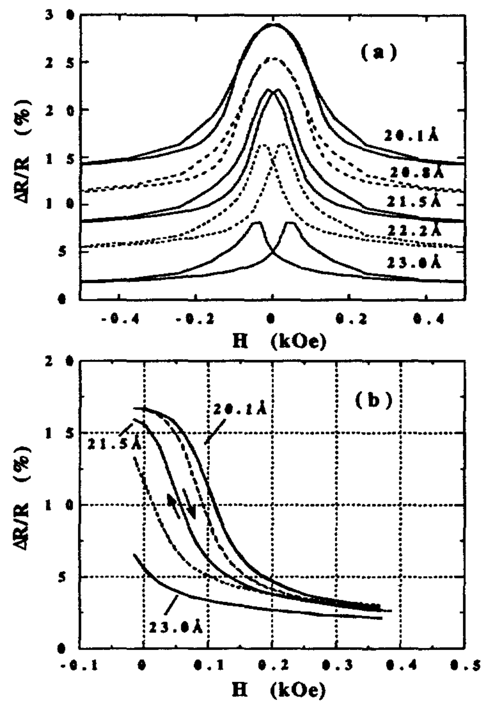

Fig. 4: (a) GMR response and (b) corresponding minor loops for Si/[Co30Å/Cut_{Cu}Å/Co4Å/Cut_{Cu}Å]$_{15}$/Cu20Å with t_{Cu} varying from 20.1 to 23.0 Å. The curves in (a) have been translated for clarity.

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