Domain phases in antiferromagnetically coupled sandwiches

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The impact of buffer stacks containing Cr/Fe sandwiches on the quality of the antiferromagnetic coupling in Co(1.2 nm)/Cu(0.83 nm)/Co(1.2 nm) sputtered trilayers has been investigated. Coupling strengths J larger than 0.4 erg/cm^2 have been realized. The completeness of the antiferromagnetic alignment of both Co layers at zero field has been probed with the soft magnetic layer in the buffer stack. No remanence could be detected, demonstrating the completeness of the AF coupling across the sandwiches. The lack in remanence is partly due to the (111) texture imposed by the buffer and polycrystallinity of the Co layers, causing low rotational friction. The freedom in the sense of rotation of the Co layers causes a dense domain configuration with domain walls having their magnetization in the centers parallel to the original saturation field H_s. This causes an increment in the magnetization component in the direction of H_s and a reduction in the resistance. The state of high domain density converts into a low density one by annihilation of domains at positive field, so that no remanence due to these domains is detected. © *1997 American Institute of Physics.* [S0021-8979(97)47708-3]

INTRODUCTION

The Co/Cu multilayer system has been intensively investigated because of the high magnetoresistive level.[1] This is partly due to the high scattering asymmetry of the Co/Cu interfaces and partly due to the completeness of the antiferromagnetic (AF) coupling in the first maximum. In many cases, the complete AF coupling is only achieved after several periods, while the first few ones are not perfect.

The recently introduced GMR sensors contain a Co/Cu/Co sandwich, the so-called AAF (artificial antiferromagnetic subsystem), for which the ideal AF alignment is prerequisite.[2] It consists of at least one detection layer which is decoupled from the AAF, i.e., this type of sensor requires the perfect AF alignment right from the first Cu spacer layer in the AAF. In this paper, we present a number of buffers, which allow the growth of AAFs that show perfect alignment at large AF coupling strength. Furthermore, a method for probing the completeness of the AF alignment is presented. Various causes of remanence are discussed and experimentally demonstrated.

EXPERIMENTAL TECHNIQUES

The AAFs presented here consisted of two 1.2 nm Co layers AF coupled through a 0.83 nm Cu layer. The samples were prepared by sputtering with a base pressure of 5×10^{-8} mbar and deposited on glass substrates. Several kinds of buffers were employed—type A: Cr(4 nm)/Fe(1.5 nm)/Cu(10 nm), type B: Cr(4 nm)/Fe(1.5 nm)/Co(0.8 nm)/Cu(10 nm), and type C: Cr(4 nm)/Fe(1.5 nm)/$Ni_{80}Fe_{20}$(1.8 nm)/Cu(10 nm). The purpose of the 10 nm thick Cu layer is to exchange decouple the AAF from the magnetic part of the buffer stack, and, in addition, to provide a smooth surface for the growth of the AAF. The samples were protected by a Cu(2 nm)/Cr(2 nm) capping. The polycrystalline Co–Cu layers are (111) textured.

The GMR signals were measured at room temperature by the standard four-point method with orthogonal sensing current and applied field **H** in the plane of the layers. The magnetization curves were measured by AGFM.

BUFFER LAYERS AND COUPLING QUALITY

As criteria for the quality of the AF coupling, we consider its strength J, the degree of completeness, i.e., the absence of defects, and the coupling distribution.[3] The use of a Fe buffer layer is known to lead to a strong and complete AF coupling in sputtered Co/Cu multilayers, which consequently exhibit high MR ratio.[1] However, the analysis of the magnetization curve is hampered by the thick Fe layer, particularly in the case of a sandwich containing two very thin Co layers.

Therefore we attempted to replace the Fe layer by a nonmagnetic one. A Cu buffer layer is known to induce rough interfaces in Co/Cu systems.[1] Cr exhibits much crystallographic resemblance to Fe and also has high affinity to the oxygen of the glass substrate. Unfortunately, the AF coupling vanishes completely for deposition on a Cr(4 nm)/Cu(10 nm) buffer, probably due to roughness. However, a tiny Fe layer (1.5 nm) between Cr and Cu reestablishes the occurrence of AF coupling (type A buffer). The buffer stacks of types B and C are also well suited and are characterized by excellent reproducibility. Types A, B, and C buffers contribute much less to the sample total magnetic moment as compared to the usual 6 nm Fe buffer. Let us briefly describe the effect of the magnetic part of the buffer on the magnetoresistive response of the sample.

In the case of an ideal isolated AF coupled system [see Fig. 1(a)], the angle φ between **H** and the magnetization **M**

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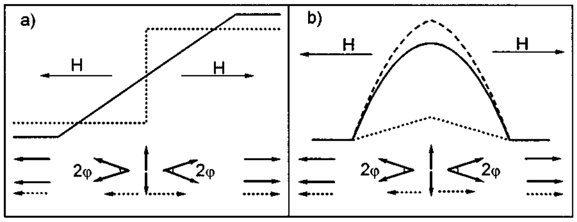

FIG. 1. Stylized $M(H)$ and $\Delta R/R(H)$ curves. In (a), the full line corresponds to the AAF and the dotted line to the soft magnetic layer. In (b), the full line is $\Delta R_{\mathrm{AAF}}(H)$, the dotted line is $\Delta R'_{\mathrm{INT}}(H)$ and the dashed line is their superposition. In each figure, the full and dotted arrows correspond to the **M** vectors within the AAF and soft magnetic layer, respectively.

of each magnetic layer of the AAF satisfies $\cos \varphi = H/H_s$ for $|H| < H_s$. The normalized GMR signal [see Fig. 1(b)] of the AAF is $\Delta R_{\mathrm{AAF}}(H) = 1 — (H/H_s)^2$. Let us now consider the situation that the AAF is no longer isolated and interacts with the magnetic layer of the buffer, which is supposed to have an ideal soft-magnetic stepwise response [see Fig. 1(a)]. The normalized GMR signal resulting from this interaction is roughly given by $\Delta R_{\mathrm{INT}}(H) = |1 - H/H_s|$ for $|H| < H_s$ and adds to $\Delta R_{\mathrm{AAF}}(H)$ [see Fig. 1(b)]. The parabolic response $\Delta R_{\mathrm{AAF}}(H)$ is modified, and the slope of the curve around $H = 0$ is related to the actual level $\Delta R'_{\mathrm{INT}}(H)$.

Figure 2 presents the GMR curves obtained for the AAF deposited on the buffer stacks of types A, B and C, respectively. A strong hysteretic behavior is observed in the signal, but we now focus on the upper $R(H)$ branch, for reasons that will be detailed further. This $R(H)$ branch presents in all cases the expected form (superposition of a parabolic curve with a triangular one). The slopes of the three curves at $H = 0$ differ significantly. It is attributed to the nature of the magnetic layer of the buffer. The aim of the three different buffer stacks is to modify the interaction between the magnetic soft layer and the AAF. The level of the signal $\Delta R_{\mathrm{INT}}(H)$ is determined by the electron scattering events of both spin-current channels at both the Co/Cu and the FM/Cu interfaces and also in the magnetic bulk of the buffer. Here FM is Fe, Co, and $Ni_{80}Fe_{20}$ for types A, B, C, respectively. The level of $\Delta R'_{\mathrm{INT}}(H)$, and consequently the slope around $H = 0$ of the total GMR curve [see Fig. 1(b)] is proportional to $(\alpha_{\mathrm{Co}} - 1)(\alpha_{\mathrm{FM}} - 1)$, where $\alpha_{\mathrm{FM}} = \rho\downarrow/\rho\uparrow$ is the effective spin-asymmetry ratio of the buffer.

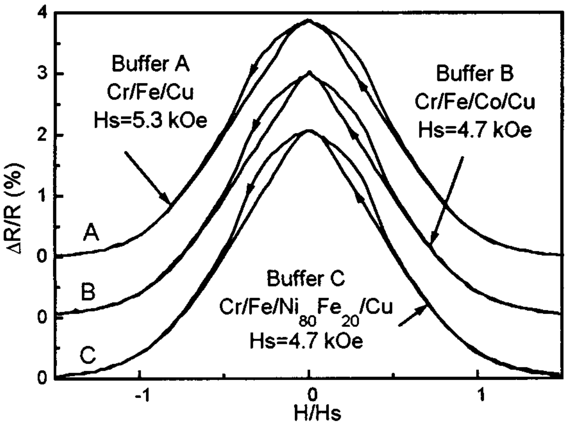

FIG. 2. The magnetoresistance signal as a function of the normalized field H/H_s for identical AAFs deposited on three types of buffer stacks. The vertical scale is the same in all cases, shifted by 1% for clarity.

As shown in Fig. 2, the slope at $H = 0$ is the largest for the type B buffer, which suggests that $\alpha_{\mathrm{Co}} > \alpha_{\mathrm{NiFe}} \approx \alpha_{\mathrm{Fe}}$. It is in accordance with the fact that the MR ratio of Co/Cu multilayers is known to be five times larger than that of $Ni_{80}Fe_{20}$/Cu and Fe/Cu.[4] However, the shape of the magnetoresistive signal of the isolated AAF is very sensitive to small variations of the spacer and magnetic layer thicknesses. If the monoatomic steps have lateral extensions larger than the lateral coherence length, the magnetoresistance curve is the superposition of several parabola, each characterized by a different saturation field.[3] The deformation of the ideal parabola can modify the slope at $H = 0$ of the total signal, whose value can thus not be used to estimate quantitatively the effective spin-asymmetry ratio of the buffer.

The magnetic layer of the buffer stack constitutes a disadvantage for the analysis of the magnetic behavior of the AAF. On the other hand, it provides a useful tool for testing the completeness of the antiparallel alignment of the Co layers at $H = 0$.

Let us now consider the case of a small lag $\Delta\varphi$, for example due to friction, in the magnetic response of the AAF, so that $\varphi = \cos^{-1}(H/H_s) - \Delta\varphi$. $\Delta R_{\mathrm{AAF}}(H)$ deviates by $2\Delta\varphi \sin(2\varphi)$ from the perfect signal. The response is mostly sensitive to this modification for φ values around ±45°±90°. On the contrary, the signal is not sensitive to the deviation from the complete antiparallel alignment of the AAF at $H = 0$ ($\varphi = 90°$), i.e., to remanence. In the case of a small lag $\Delta\varphi$, $\Delta R_{\mathrm{INT}}(H)$ deviates by $\Delta\varphi \sin \varphi$ from the perfect signal. The effect of $\Delta\varphi$ on the GMR is the largest for φ values around 90°, i.e., near H=0. A sudden jump in the GMR signal will occur upon switching the soft magnetic layer. $\Delta\varphi$ in this example originates in homogeneous friction in the AAF. It is obvious that any other source of remanence in the AAF will produce a similar effect.

Let us focus on the experimental magnetoresistive response of the samples, and particularly near $H = 0$, for example in the case of an AAF deposited on the buffer stack of type B (Fig. 3). The AAF presents a large AF coupling ($J = 0.4$ erg/cm^2, and even larger has been achieved). The buffer has also been grown without AAF on top, to separately investigate its $M(H)$ response. The Fe(1.5 nm)/Co(0.8 nm) bilayer switches at about -50 Oe [inset in Fig. 3(b)]. As shown in the inset in Fig. 3(a), the $R(H)$ reduces upon switching the detection layer, indicating that the mean **M** of the AAF has already changed sense, i.e., the remanence of the trilayer is negligibly small. This is confirmed by the $M(H)$ measurement in Fig. 3(b).

The Co/Cu/Co sandwich deposited on type A or C buffers also presents a strong AF coupling strength $J \approx 0.4$ erg/cm^2) and a complete AF alignment at $H = 0$. Noting, that most multilayers only exhibit perfect AF coupling after growing several periods, the present results demonstrate the excellent quality of the buffers.

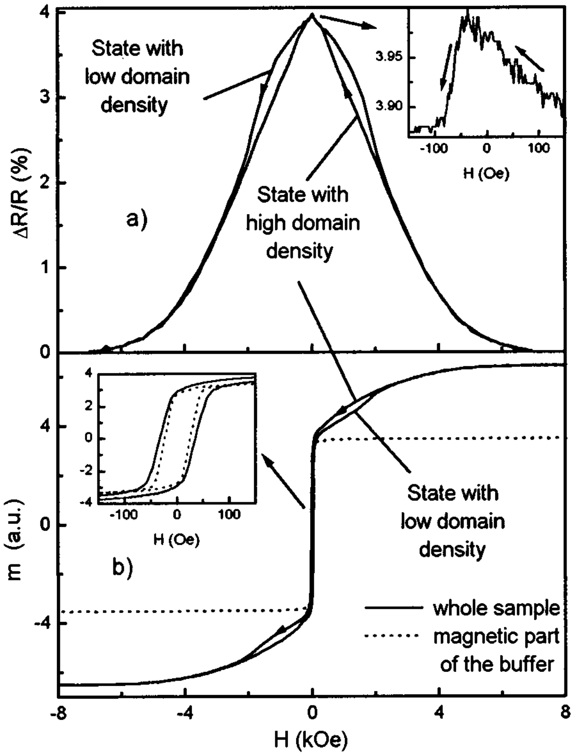

FIG. 3. Magnetoresistance (a) and magnetization (b) curves of the sample Co/Cu/Co on type B (Cr4 nm/Fe1.5 nm/Co0.8 nm/Cu10 nm) buffer stack. In (b), the dotted lines show the magnetization of the soft magnetic Fe1.5 nm/Co0.8 nm bilayer, with no AAF on top. The insets detail the signals between 150 and −150 Oe.

DOMAINS IN AF COUPLED SYSTEMS

Various branches are recognized in both the GMR and $M(H)$ curves. The branch with the lowest $R(H)$ occurs when reducing **H** from positive saturation towards zero in Fig. 3(a). The relatively low resistivity ρ is attributed to the development of a dense domain structure, which originates in the freedom in the sense of the rotation of the **M** of the AAF. Upon reducing H, the **M**'s of both AAF-magnetic layers rotate in opposite directions until they reach an AF alignment at $H=0$. Because of polycrystallinity, there is no global anisotropy and at zero field, the AF alignment should be perpendicular to the original **H**. The **M** in a specific layer has the freedom to rotate either clockwise or anticlockwise. Probably, asymmetries in the local anisotropy energies between both AAF-magnetic layers determine the local sense of rotation. Consequently, domains distinguishing themselves by the sense of rotation of **M** develop. Domain walls separate the regions with opposite rotation sense. The moments in the middle of the walls always lie in the direction of the original saturation field. The walls in both magnetic layers are just above each other because of their magnetostatic coupling. The width of these walls is of the order or larger than the longest mean free path of the electrons so that the walls constitute channels with reduced ρ. In other words, at some given field, ρ is lower at the domain walls because of the parallelism of the moments, compared to the hypothetical configuration with uniform **M** in each of the layers. The higher $R(H)$ branch is characterized by a much lower wall density due to irreversible domain annihilations (as will be explained). The lower $R(H)$ curve in Fig. 3(a) and the branch with the higher mean moment along **H** in Fig. 3(b) correspond. Remembering that the moments in the middle of the domain walls always lie in the direction of the original **H**, the $M(H)$ branch with the high domain-wall density should lie above its pendant.

The domains constitute states of high energy that become unstable when the domain-wall energy increases. This energy increases strongly upon reducing H since the domain-wall angles grow. The smaller domains in regions with strong AF coupling, i.e., with high wall angles and wall-energy density, collapse first. The angle between the **M**'s of both layers of the AAF grows at the former wall sides, and, as a consequence, the local resistivity is increased. After reducing H to zero, the domain density is diminished to a low level. Increasing H to the negative saturation leads to the occurrence of the high $R(H)$ branch [Fig. 3(a)] and to the low $M(H)$ branch [Fig. 3(b)]. In the previous section, we have focused on the upper $R(H)$ branch. The corresponding magnetic configuration (low density of domain walls) exhibits much resemblance with the ideal configuration of Fig. 1 (single domain layers), provided that the mean size of the domains is large enough.

CONCLUSION

The use of different buffers has allowed us to obtain a very high coupling quality in sputtered (111) Co/Cu/Co sandwiches with complete antiferromagnetic alignment of the Co layers at zero field. The buffer provides a useful tool to probe by means of GMR signal the amount and direction of remanence of the Co/Cu/Co part.

The various branches in both the GMR and $M(H)$ signals correspond to a general phenomenon originating in the freedom of the sense of rotation of the Co magnetization upon reducing **H** from saturation. The studied samples are magnetically isotropic and the occurrence of the state with high domain density might be avoided when a global anisotropy is present which differs for both AAF layers.

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