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Perpendicular anisotropy and oscillatory interlayer coupling in $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}$ bilayers on Rh(001)

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Tetragonal distortion in $Fe_{0.5}Co_{0.5}$ alloy films grown epitaxially on Rh(001) substrates results in an easy magnetization axis perpendicular to the film plane up to the thickness of 17 ML. The distortion is supported by a Rh-overlayer; thus the strong perpendicular anisotropy can be kept when another $Fe_{0.5}Co_{0.5}$ film is grown on top of the $Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ structure. Depending on the thickness of the Rh spacer, the top and bottom $Fe_{0.5}Co_{0.5}$ films are either ferro- or antiferromagnetically coupled. The net magnetization of the antiferromagnetically coupled $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}$ bilayer switches at the field which depends on the difference between magnetizations of both the $Fe_{0.5}Co_{0.5}$ layers. The final covering of the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ structure with Rh increases the switching field. The effect is explained by a locally enhanced magnetization in the $Rh/Fe_{1-x}Co_x$ interfaces. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3065984]

The phenomenon of interlayer exchange coupling was discovered many years ago and has received a lot of attention since then. Depending on the thickness, a nonmagnetic (NM) spacer can mediate either a ferro- (FM) or antiferromagnetic (AFM) exchange coupling between two FM films.[1] The presence of uniaxial anisotropy ensures a discrete switching behavior of the magnetization simplifying the shape of the hysteresis loop, in particular for the AFM-coupled FM/NM/FM structure. This allows to observe many interesting phenomena such as a surface spin flip transition in artificial antiferromagnets.[2] The combination of uniaxial magnetic anisotropy and AFM interlayer coupling is interesting for applications because such systems are sensitive to magnetic fields along the easy axis of magnetization.

Due to the simplicity in the synthesis and the availability of material, Fe-based alloys are frequently used for magnetic applications. Often Fe–Co alloys are of interest, in particular when high magnetic moment materials are required.

As a perpendicularly magnetized FM/NM/FM bilayer we propose a fully epitaxial $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ exchange-coupled system. In such system both $Fe_{0.5}Co_{0.5}$ layers exhibit an easy magnetization axis perpendicular to the sample plane[3,4] while Rh spacer mediates the interlayer coupling. A strong uniaxial magnetic anisotropy is predicted for $Fe_{0.5}Co_{0.5}$ alloys under a proper tetragonal distortion of $c/a=1.22$.[5] In such tetragonally distorted $Fe_{0.5}Co_{0.5}$ alloy films the crystal field locates the electronic states near the Fermi level (E_F) with one being below E_F and the other above E_F with an energy separation smaller than in the cubic symmetry lattice.[5] In our case, the $Fe_{0.5}Co_{0.5}$ alloy films are tetragonally distorted due to their pseudomorphic growth on the mismatching Rh(001) substrate. The resulting perpendicular magnetic anisotropy is strong enough to clearly outbalance the shape anisotropy. The easy magnetization axis remains perpendicular to the film plane above the thickness up to which the tetragonal distortion is kept, i.e., up to 17 ML (monolayer).[3,4,6] Since the Rh spacer layer grows epitaxially and keeps its bulk lattice constant, the top $Fe_{0.5}Co_{0.5}$ layer is tetragonally distorted like the bottom $Fe_{0.5}Co_{0.5}$ layer, and thus is also expected to exhibit a strong perpendicular anisotropy.

The $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ system contains $Fe_{0.5}Co_{0.5}$ alloy films which are easy to grow and show a large saturation magnetization. This is very different from the Pt/Co (Ref. 7) and Pd/Co (Ref. 8) multilayers with only 4 Å thick Co films sandwiched between Pt or Pd spacers. Such multilayers, which are often used as exchange-coupled systems of perpendicular anisotropy, are complex to grow and their magnetization per volume unit of the structure is small.

It is known that coupling through the Rh spacer layer can be by two orders of magnitude stronger than e.g., in the case of Cu or Au spacers.[9] For the AFM-coupled $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ bilayers with a strong uniaxial anisotropy this simply means that the saturation field H_s, i.e., the field at which both magnetizations are oriented along the applied field, is large. This could allow the detection of the switching of the net magnetization of the bilayer (at the field called "bilayer coercivity," H_c) even if the magnetizations of both FM layers are very similar (H_c is large in this case). A schematic of the magnetization contributions to the signals measured from the AFM-coupled structures is shown in Fig. 1.

The aim of this study is to show that a bilayer (multilayer) system exhibiting a perpendicular easy magnetization axis can be realized by growing $Fe_{0.5}Co_{0.5}$ alloy films on Rh(001) and separating them with a Rh buffer layer. This system shows a large saturation field (>1 T), thus it allows a detailed analysis of the bilayer coercivity. In particular, it will be shown that valuable pieces of information can be obtained for the $Rh/Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ structure, even on the $Fe_{0.5}Co_{0.5}/Rh$ interface mag-

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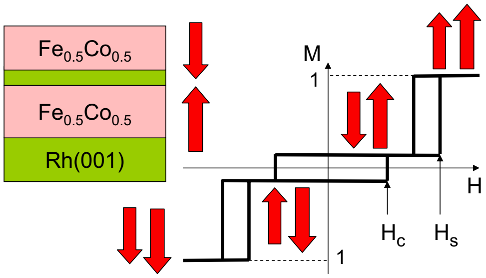

FIG. 1. (Color online) Schematic explaining sample structure and magnetization (Kerr ellipticity) contributions to the Kerr ellipticity signal in the case AFM coupling between the $Fe_{0.5}Co_{0.5}$ films.

netism, by applying *in situ* magneto-optical Kerr effect (MOKE) measurements.

The $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ bilayers were grown at room temperature (RT) by molecular beam epitaxy in a multichamber ultrahigh vacuum system with a base pressure better than 5×10^{-11} mbar and less than 2×10^{-10} mbar during deposition. The Rh(001) substrate was prepared using sputtering-annealing cycles. The quality of the sample was checked by Auger electron spectroscopy and by scanning tunneling microscopy until a clean surface with nearly equidistant, parallel monatomic steps were obtained. The $Fe_{0.5}Co_{0.5}$ films were grown using two effusion cells as described previously.[6] The Rh spacers were grown from a Rh rod of high purity by electron bombardment.

Magnetic properties were probed by utilizing the *in situ* MOKE, for 1.85 eV photon energy of *s*-polarized light in nearly polar geometry (incidence angle of 69° to the sample normal) at varying temperature (down to 5 K) and an external magnetic field up to 0.7 T.

Magnetic properties of the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ bilayers were probed with *in situ* MOKE by measuring the Kerr ellipticity. The polar Kerr loops are rectangular with 100% remanence magnetization clearly showing perpendicular easy magnetization axis of the anisotropy of the system. The Kerr ellipticity loops shown in Fig. 2 were measured at RT for a single $Fe_{0.5}Co_{0.5}$ film (6 ML thick) on Rh(001), and after the structure was completed with the top $Fe_{0.5}Co_{0.5}$ film of the same thickness. The thickness of the Rh spacer layer, 7 ML in this case, corresponds to the FM coupling between the $Fe_{0.5}Co_{0.5}$ layers. The polar Kerr ellipticity measured for the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}$ bilayer is much larger than that measured from the single $Fe_{0.5}Co_{0.5}$ film because both $Fe_{0.5}Co_{0.5}$ films contribute to the polar Kerr signal (however both $Fe_{0.5}Co_{0.5}$ do not contribute equally).

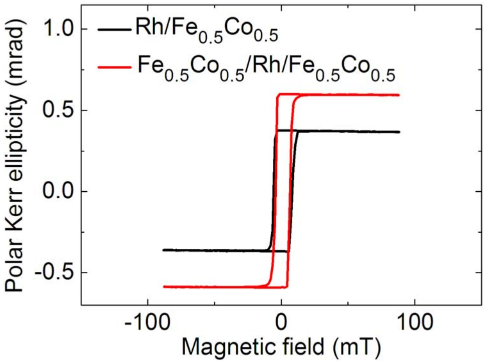

FIG. 2. (Color online) Polar Kerr ellipticity loops measured at RT for $Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ and $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ samples. The thickness of the Rh layer separating both $Fe_{0.5}Co_{0.5}$ films is 7 ML which corresponds to the FM coupling. The loop of the bilayer is rectangular showing 100% magnetization in remanence. The $Fe_{0.5}Co_{0.5}$ films do not contribute equally to the total Kerr signal since they are not of the same thickness.

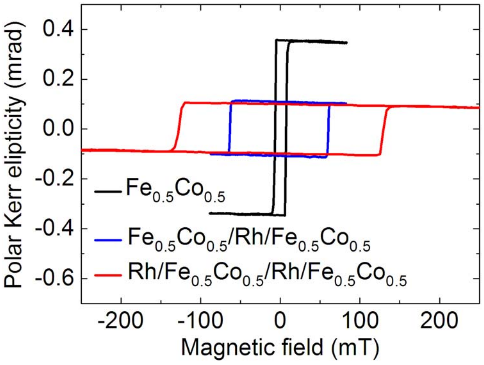

FIG. 3. (Color online) Polar Kerr ellipticity loops measured at RT for $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$. The Rh spacer layer is 5 ML thick, which corresponds to AFM coupling. The thickness of both $Fe_{0.5}Co_{0.5}$ layers is not the same, thus the net magnetization differs from zero. The coercivity of the bilayer is large (of the order of 70 mT) because the magnetizations of both layers differ not much. A final covering of the structure with Rh results in a strongly increased coercivity up to about 130 mT. This is due to an enhanced net magnetization at the top $Rh/Fe_{0.5}Co_{0.5}$ interface (see text) which makes the magnetizations of both $Fe_{0.5}Co_{0.5}$ layers very similar (for exactly the same magnetizations coercivity approaches infinity). The loop of single $Fe_{0.5}Co_{0.5}/Rh(001)$ film is shown for comparison.

The Kerr ellipticity loops measured at RT for the AFM-coupled $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ system are shown in Fig. 3. The loop measured for the single 7 ML thick $Fe_{0.5}Co_{0.5}$ film on Rh(001) is compared to the loop obtained after the structure is completed with the top $Fe_{0.5}Co_{0.5}$ film 6 ML thick. The $Fe_{0.5}Co_{0.5}$ films are AFM-coupled across a 5 ML thick Rh spacer layer. Finally, the figure is supplemented with the loop measured after the whole structure was covered with Rh. Is the polar Kerr loop measured after the bilayer completed, it shows a much smaller ellipticity than that measured from the single $Fe_{0.5}Co_{0.5}$ film, however, the net ellipticity is not equal zero since the magnetizations of both layers are not the same.

Due to the strong AFM coupling the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}$ bilayer saturates at a relatively high magnetic field (not shown in Fig. 3). At low fields, the strongly AFM-coupled $Fe_{0.5}Co_{0.5}$ films in the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}$ structure switch together. They keep their AFM coupling, i.e., only the net magnetization switches to follow the field direction, whereas the $Fe_{0.5}Co_{0.5}$ layers remain AFM-coupled. The switching field, H_c, is related to the difference between magnetizations of both the $Fe_{0.5}Co_{0.5}$ layers and has nothing to do with the strength of the AFM coupling. The lowest H_c is expected for the FM/NM/FM bilayer of very different magnetizations of the FM layers, which corresponds in this case to the coercivity of the thicker layer. When both FM layers of the AFM-coupled bilayer approach the same magnetization, H_c increases rapidly and thus becomes extremely sensitive to any change in the net magnetization of the bilayers. For exactly the same magnetizations the bilayer coercivity approaches infinity.[10] Usually the loop related to the switching of the net magnetization is not visible for AFM-coupled films of similar magnetizations since H_c is larger than the saturation field H_s.

It is known that in many cases the covering of the FM material with an NM cover results in changed magnetic properties at the FM/NM interface. In general, two effects could be expected: (1) an induced magnetic moment in the interfacing atomic layer/layers of the NM cover; this could happen, in particular, for the elements which are supposed to be close to fulfill the Stoner criterion of ferromagnetism, such as Pd (Ref. 11) or Rh (Ref. 12) (which can be FM or AFM coupled to the FM layer), and (2) an increased or decreased magnetic moment at the interfacing atomic layer/layers of the FM layer due to electronic hybridization with the NM cover. Usually, both effects are limited to the very interface region. Both the induced moment in the NM cover and the increased (or decreased) moment in the FM layer are rather small. Nevertheless, such small changes of the magnetization due to covering can drastically change the coercivity if the FM layer is AFM coupled to another FM layer of similar magnetization.

In the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ AFM-coupled bilayer, the thicknesses of the bottom and top $Fe_{0.5}Co_{0.5}$ layers are 7 and 6 ML, respectively. The top $Fe_{0.5}Co_{0.5}$ layer has only one interface with Rh, whereas the bottom one has two such interfaces which can also affect the layer magnetization (see Fig. 1). These little different magnetizations of both $Fe_{0.5}Co_{0.5}$ layers result in a large coercivity of the bilayer which is of the order of 70 mT (Fig. 3). Yet such a large coercivity of the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ bilayer is still smaller than the saturation field H_s. When the external magnetic field is applied along the easy magnetization axis, the net magnetization of the bilayer switches to the field direction at a well defined field H_c. The exchange coupling across Rh spacer layer is known as the strongest among all others NM spacers investigated.[9] Thus, H_s is easily expected to be larger than H_c, which makes the $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}$ system attractive for H_c analysis.[10] The final covering of the structure with Rh does not change remarkably the intensity of the Kerr signal, however it strongly increases the bilayer coercivity H_c up to about 130 mT.

The increased bilayer coercivity could be caused by the enhanced magnetization of the top $Rh/Fe_{0.5}Co_{0.5}$ layer after covering it with Rh, which makes the magnetizations of both $Fe_{0.5}Co_{0.5}$ layers very similiar. As mentioned before, the coercivity of AFM-coupled bilayer increases strongly when both FM layers approach the same magnetization. Such an enhanced magnetization is in line with the expected induced and enhanced magnetic moment in Rh and $Fe_{0.5}Co_{0.5}$ films, respectively. The induced magnetic moment in Rh is reported, e.g., for Co/Rh (Ref. 12) interface as well as for Fe–Rh (Ref. 13) and Co–Rh (Ref. 14) alloys. However, to our best knowledge there is no report on the Rh/Fe–Co interface and on the coupling configuration in this case. It should also be mentioned that there is another explanation such as an interface intermixing, leading to a locally increased magnetization which cannot be excluded.

One can conclude that the coercivity of the AFM-coupled bilayer can provide valuable information on these magnetic phenomena similar to the coercivity of the FM coupled Co/Pt multilayers.[15] Magneto-optical quantities such as ellipticity and rotation are strongly influenced by the optical properties of the system elements (substrate, spacing layers, etc.). In particular, a magneto-optical response from a FM layer can depend on the layer position within the multilayer structure and can be different from what is measured by magnetometry. However, coercivity is measured by MOKE equivalently to the magnetometry techniques.

The combination of proper tetragonal distortion and a properly adjusted Fermi level results in a strong perpendicular anisotropy in the $Fe_{0.5}Co_{0.5}$ films grown on Rh(001). Since the anisotropy for a fixed composition depends only on distortion, the Rh spacer layer supports perpendicular anisotropy in $Fe_{0.5}Co_{0.5}/Rh/Fe_{0.5}Co_{0.5}/Rh(001)$ bilayers (or multilayers). Moreover, the Rh spacer layer introduces an interlayer coupling which forces the magnetizations of the $Fe_{0.5}Co_{0.5}$ layers to be oriented parallel or antiparallel depending the coupling is FM or AFM, respectively. The increased coercivity of the AFM-coupled bilayer after covering with Rh can be due to the enhanced magnetization of the top $Fe_{0.5}Co_{0.5}$ layer by covering which could make the magnetizations of both $Fe_{0.5}Co_{0.5}$ layers very similar.

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