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Using antiferromagnetic/ferromagnetic bilayers as detection layers in magnetic tunnel junctions

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It is shown that the association of an antiferromagnetic material with a ferromagnetic material in an exchange-coupled bilayer, often used in spintronic devices as a magnetic reference or pinned system, can be used as a detection layer in magnetoresistive sensors. The magnetic response is shown to be reversible and linear in an adjustable field window. The sensitivity is studied as a function of temperature. © 2003 American Institute of Physics. [DOI: 10.1063/1.1630171]

Since its discovery by Meiklejohn and Bean,¹ the exchange bias exerted by an antiferromagnetic (AF) layer on a ferromagnetic (FM) layer in close contact (in an AF/FM bilayer), is the focus of many theoretical and experimental studies.² Even if a full theoretical description of the phenomena has not yet emerged, it has been used from the applied point of view especially to “pin” the magnetization of reference layer in spintronic devices. In the following, we aim to show that AF/FM bilayers are also good candidates to design original sensing layers to get a linear variation of resistance with applied field in spin valves [giant magnetoresistance (GMR) structures], magnetic tunnel junctions [tunneling magnetoresistance (TMR) structures] and more sophisticated “spin electronic” devices.

As regards magnetic field sensing, linearity and reversibility of the analogical signal are key issues to make reliable sensors. Therefore, in the case of GMR and TMR, a crossed magnetizations pattern has been proposed^{3,4} and used in this study. The hard reference layer magnetization, m_h , is oriented and locked by its magnetic anisotropy, $K_{F,h}$, along the field sensitive direction, H , while the sensing layer is constructed to have its magnetization, m_s , perpendicular to m_h (Fig. 1). Then, linearity and reversibility are given by the response of m_s with respect to H . This requires a coherent rotation of the magnetization under an external magnetic field. Up to now, this has been done using (i) a bias field generated by a specific circuit,⁵ (ii) the shape anisotropy induced by a step bunched substrate,⁴ or (iii) the shape anisotropy induced in the sensing layer by microtechnological steps.⁶ These suggested solutions have their specific defaults: power consumption for (i), limited integration on Si chips for (ii), and need of small sensing elements and/or sensing element on the top of the multilayer stack for (iii).

Those problems can be circumvented by the use of an AF/FM bilayer if the anisotropy axis, K_{AF} , of the AF layer is built up perpendicular to $K_{F,h}$ (Fig. 1). This is easily done with a suitable thermal annealing. Considering the FM layer in a single domain state, the energy of the FM moment per surface unit with the applied field perpendicular to K_{AF} is given in a simple model by

$$E = -M_{sF}H \sin(\Phi) - J \cos(\Phi) + K_{F,s}t_F \sin^2(\Phi), \quad (1)$$

where $K_{F,s}$, M_{S} , and t_F are, respectively, the anisotropy axis, the saturation magnetization, and thickness of the FM layer and J is the surface exchange coupling between the FM and AF layers. The angular position of the FM moment in an applied field proceeds from the energy minimization. In order to get an analytic solution, the anisotropy of the FM layer has been neglected. Then, the component of FM magnetization along the applied field, m_{\parallel} , is given by

$$m_{\parallel} = \sin(\Phi) = \cos(\Theta) = \sin \left[\arctg \left(\frac{M_{sF} H}{J} \right) \right]. \quad (2)$$

Finally, the resistance, $R(H)$, of a tunnel junction or spin valve with the geometry depicted in Fig. 1 is given by

$$R(H) = \frac{R_P + R_{AP}}{2} + \frac{R_P - R_{AP}}{2} \sin \left[\arctg \left(\frac{H}{H_{ex}} \right) \right], \quad (3)$$

where R_P and R_{AP} are the junction or spin valve resistances for parallel and antiparallel alignments of m_s and m_h , respectively, and $H_{ex} = J/(M_{sF})$ is the so-called exchange field. Then, for a fixed *electric sensitivity* given by $(R_P - R_{AP})/2$ and tunable by the choice of junction or spin valve multilayer materials, the low field *magnetic sensitivity* of the sensor is given by $1/H_{ex}$.

The results of Eqs. (2) and (3) were checked experimentally with multilayers deposited onto float-glass substrates by sputtering Ir₂₀Mn₈₀ (IrMn), Fe₂₀Ni₈₀ (Py), Co, and Ta targets

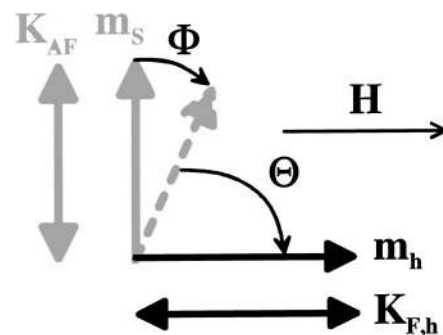


FIG. 1. Schema showing the relative orientations of the anisotropy axes of (i) the AF layer (K_{AF}) in contact with the magnetic sensing layer with magnetic moment m_s , (ii) the FM layer ($K_{F,h}$) with magnetic moment m_h . At zero applied field H , m_s is along K_{AF} and m_h along $K_{F,h}$. When the applied field along $K_{F,h}$ increases, m_s rotates towards H .

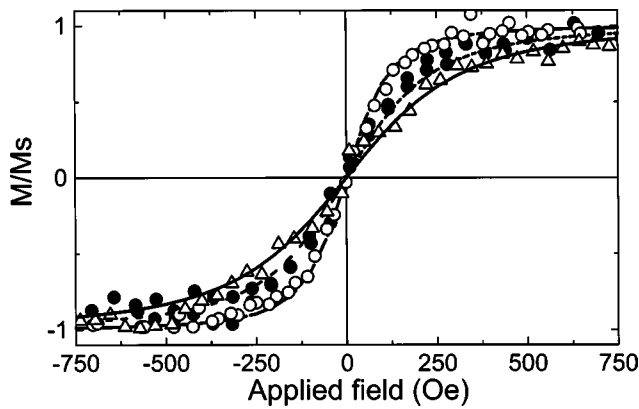


FIG. 2. Kerr rotation hysteresis loop measured in the longitudinal geometry with an applied field perpendicular to K_{AF} on glass/Ta (5 nm)/Py (x nm)/IrMn (10 nm)/Ta (5 nm) multilayers: $x=10$ nm (\circ), $x=5$ nm (\bullet), and $x=3.7$ nm (\triangle). Lines correspond to calculations made using Eq. (2) without any adjustable parameter.

mounted on magnetron cathodes. Each multilayer is deposited at an operating Ar pressure fixed to 5×10^{-3} mbar and the substrates are maintained at room temperature. After growth, samples were annealed during 30 min at 200 °C with a 300 Oe in plane applied magnetic field in order to setup the IrMn exchange biasing. The structure and the microstructure of all these multilayer stacks were checked in a previous study⁷ and it has been shown that IrMn, and Py or Co are highly crystallized with the (111) planes parallel to the surface. For IrMn thicknesses above 5 nm, exchange occurs and the surface exchange coupling energies have been computed from the shift of the FM layer hysteresis loop, H_{ex} , when H was applied along K_{AF} .

In a first step, Kerr rotation hysteresis loop measured in the longitudinal geometry with an applied field perpendicular to K_{AF} on glass/Ta (5 nm)/Py (x nm)/IrMn (10 nm) Ta (5 nm) multilayers are reported in Fig. 2. Independently on x , it appears that the curves are fully reversible in the entire measure field range. Furthermore, in a more restricted field window, the response is linear. Calculations made using Eq. (2) and values of J measured on the same samples from Ref. 7 could accurately reproduce the experimental measurements without any adjustable parameter.⁸ Those results assert that AF/FM bilayers can be used as detection layers and that the magnetic sensitivity for a given material can be changed by modifying J or t_F as shown theoretically with Eq. (2) and experimentally with Fig. 2 (in this last case, only t_F was modified). The AF/FM bilayer can *a priori* be placed under or over the tunnel barrier but it has been shown that in this last configuration,⁹ the blocking temperature of the AF layer is reduced due to a loss of texture over the tunnel barrier, inducing then a reduction of the sensor working temperature window. Therefore, the AF/FM bilayer has been included in the bottom electrode.

In order to promote texture, the AF/FM bilayer has been grown on glass substrate on top of a Ta (5 nm)/Py (10 nm) buffer layer. The magnetic sensitivity as a function of temperature of a IrMn (7.5 nm)/Py (5 nm) bilayer has been checked by anisotropic magnetoresistance (AMR) measurements on a glass/Ta (5 nm)/Py (10 nm)/IrMn (7.5 nm)/Py (5 nm)/Ta (5 nm) sample. The measurement geometry has been well established using lithography and ion beam etching. The

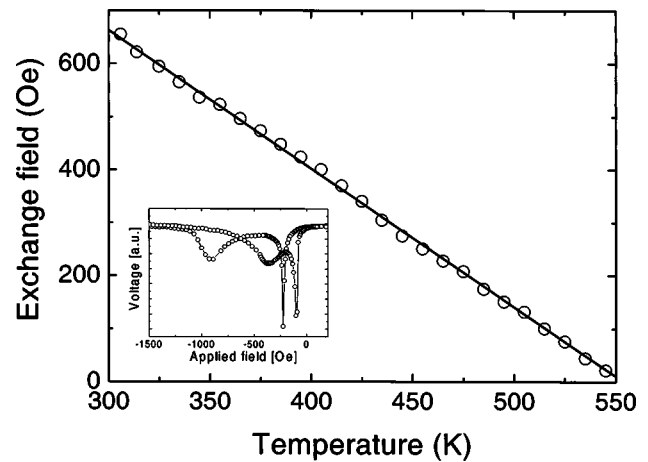


FIG. 3. Exchange field H_{ex} evaluated as a function of temperature for the IrMn (7.5 nm)/Py (5 nm) interface in a glass/Ta (5 nm)/Py (10 nm)/IrMn (7.5 nm)/Py (5 nm)/Ta (5 nm) sample. Inset: an AMR measurement made at 310 K where peaks correspond to the reversal of both Py layers.

current flows parallel to the exchange field direction which in turn is parallel to the applied field. From the AMR peaks corresponding to the reversal of both Py layers, the evolution of H_{ex} with temperature at the IrMn (7.5 nm)/Py (5 nm) interface could be measured and is reported in Fig. 3. As expected from previous studies,² H_{ex} has a linear decrease with temperature. So, as temperature increases, the magnetic sensitivity of the sensor increases but the measurement field range decreases. Indeed, saturation occurs at lower applied fields. More important, since H_{ex} varies linearly with temperature, the variation of magnetic sensitivity with temperature can easily be corrected with an appropriate electronic treatment of the sensor output.

Finally as a proof of concept, the AF/FM bilayer has been integrated in a magnetic tunnel junction made from a glass/Ta (5 nm)/Co (10 nm)/IrMn (10 nm)/Co (10 nm)/Al₂O₃ (1.5 nm)/Co (20 nm)/Pt (5 nm) multilayer stack. Here, the sensing layer is the IrMn (10 nm)/Co (10 nm) bilayer with Co in contact with the tunnel barrier. A simple Co (20 nm)/Pt (5 nm) reference layer has been used even if its low $K_{F,h}$ does not promote its magnetization stability against high fields. This point has to be addressed in a next step to make a high field sensor. The central point here is to prove the concept of AF/FM field sensing bilayer. The annealing procedure was made such to orient K_{AF} of the IrMn layer perpendicular to $K_{F,h}$ of the Co (20 nm)/Pt (5 nm) layer (Fig. 1). A four step process of lithography, ion beam etching, insulator, and metal deposition has been used to shape the multilayer stack into a tunnel junction for current perpendicular to film plane measurements. The resistance of the tunnel junction has been measured with the field applied parallel to $K_{F,h}$ (Fig. 4, -○-).

As expected from Fig. 2, the variation of resistance is linear and reversible for applied fields smaller than the coercive field of the Co (20 nm) layer (60 Oe in this case). This definitely asserts that AF/FM bilayers can be used as detection layers in spin valves or magnetic tunnel junctions to make magnetic field intensity sensors. The experimental curve of Fig. 4 could be simulated (heavy line) using Eq. (3) and parameters extracted from previous studies, Ref. 7. In this proof of concept, a total sensitivity, including magnetic

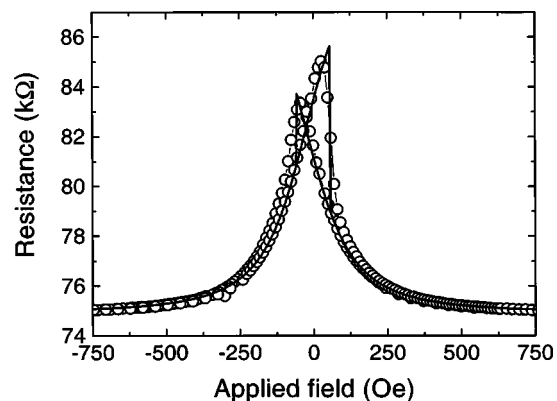


FIG. 4. Resistance of a magnetic tunnel junction made from a glass/Ta (5 nm)/Co (10 nm)/IrMn (10 nm)/Co (10 nm)/Al₂O₃ (1.5 nm)/Co (20 nm)/Pt (5 nm) multilayer stack (○-○). The field is applied parallel to $K_{F,h}$ and applied voltage equals 10 mV. The curve could be simulated (heavy line) using Eq. (3) with $J=0.23 \text{ erg cm}^{-2}$, $M_S=1420 \text{ emu cm}^{-3}$, $t_F=10 \text{ nm}$, $R_{AP}=89\,750 \text{ } \Omega$, $R_P=74\,900 \text{ } \Omega$. Those parameters have been extracted from previous studies (Ref. 7). Furthermore, $K_{F,h}=4 \times 10^4 \text{ erg cm}^{-3}$ and a bias field of -25 Oe have to be introduced in Eq. (3).

and electric sensitivity, of around $5 \times 10^5 \text{ V/TA}$ could be achieved. However, a bias field of -25 Oe has to be introduced in Eq. (3) in order to account for the field asymmetry. The origin of this bias field is at present under study.

In this letter, we give theoretical and experimental proofs that the association of an antiferromagnetic material with a ferromagnetic material in a bilayer can be used as a detection

layer in magnetic tunnel junctions in order to generate a highly linear and reversible analogical signal. It is shown that the sensitivity of the sensor can be tuned by changing the FM material parameters and its linear variation with temperature can be easily compensated. AF/FM bilayers appear then as alternative sensing layers to commonly used technological solutions.

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