

## MAGNETO-RESISTANCE AND INDUCED DOMAIN STRUCTURE IN TUNNEL JUNCTIONS

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### ABSTRACT

Magnetization reversals in sputtered Co electrodes of a magnetic tunnel junction are studied using transport measurements, magneto-optic Kerr magnetometry and microscopy. Using the tunnel magneto-resistive effect as a probe for micromagnetic studies, we first evidence the existence of an unexpected domain structure in the soft Co layer. This domain structure originates from the duplication of the domain structure of the hard Co layer template into the soft layer via ferromagnetic inter-electrode coupling. A detailed analysis of the kerr microscopy images shows that all features appearing in the variation of tunnel resistance as a function of the applied field are associated to the domain phase evolution of each electrode. By tailoring the magnetic properties of the hard Co layer, we have demonstrated that the appearance of the domain duplication is driven by the magnetic anisotropy of the hard layer. Finally, a brief theoretical description of the domain duplication process allows us to extract the main parameters governing the effect.

### INTRODUCTION

The increasing interest in magnetic tunnel junctions (MTJs) for spin electronic devices requires the understanding and the control of the magnetic properties of their ferromagnetic (FM) electrodes. A coupling between the two electrodes of the MTJ takes usually place due to their proximity. These interactions between a magnetically hard (reference) and a soft (detection) layer are of particular importance as they influence the reversal characteristics of the FM layers, and thus, the magneto-resistive behavior of the tunnel device. We illustrate explicitly the effect of the magneto-static coupling on the transport and magnetic properties of those systems.

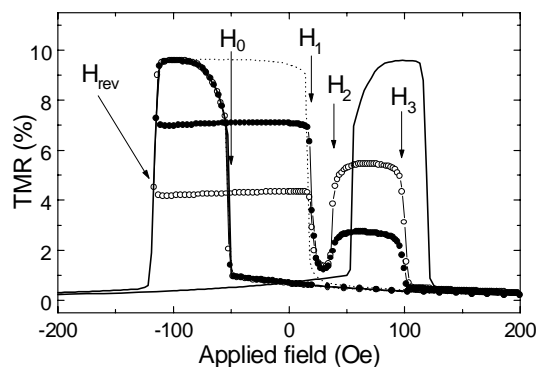
### EXPERIMENTAL DETAILS

For this purpose, we prepared Glass/Co(10nm)/Al( $e_{Al}$  nm,  $t_{Ox}$  nm)/Co( $e_{Co}$  nm)/Co\* (20nm) cross like tunnel junctions by using sputtering and *ex situ* changed shadow masks. Details on the junction fabrication (oxidation process to make the AlO<sub>x</sub> tunnel barrier, geometry for CCP measurements...) can be found elsewhere [1,2]. When Co is deposited at low Ar pressure ( $5 \times 10^{-3}$  mbar), the grain diameter is less than 2nm and the magnetization reversal of a Co(10nm) layer is sharp with nucleation and propagation of domain walls [3]. In addition, this low pressure process leads to the appearance of an anisotropy axis due to the geometry of the deposition. When the Ar pressure increases up to an optimum, equal to  $1.5 \times 10^{-2}$  mbar, the grain size and the coercive field increase up to a maximum. In this case,

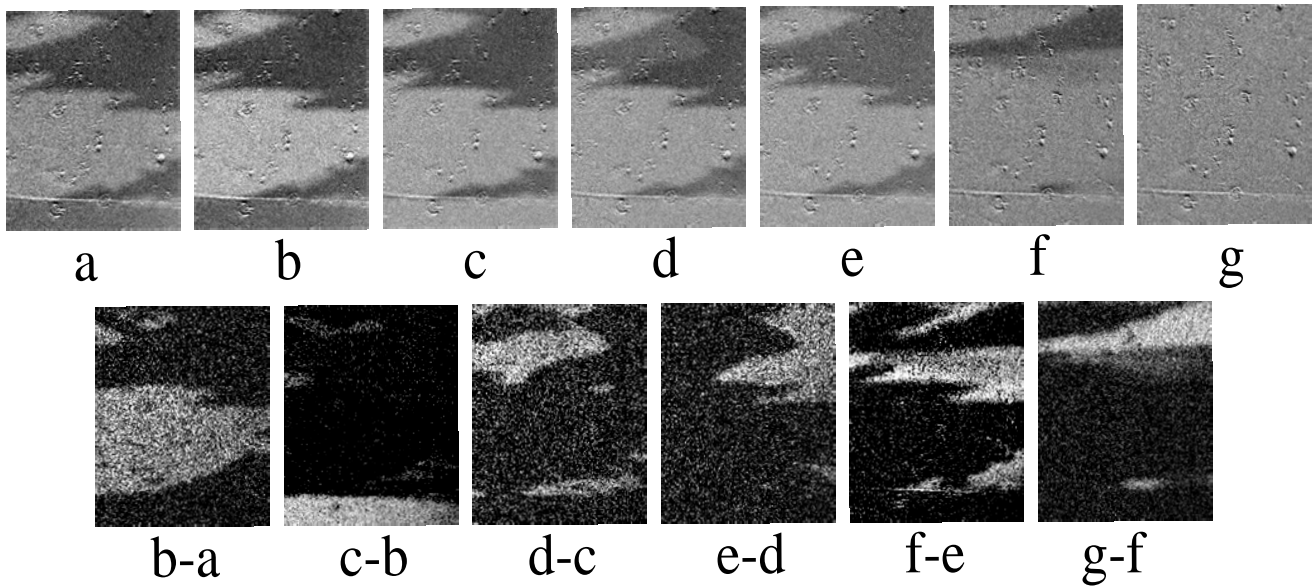
the magnetization behavior is consistent with a reversal occurring through the appearance of ripples domain structures [4]. More important, the magnetic anisotropy stabilized at low pressure completely disappears. Then, in a single  $\text{Co}^*$ (20nm) layer where  $\text{Co}^*$  is relative to high Ar pressure, magnetization reversal occurs only by rotation and the magnetization cycle is fully isotropic in the plane of the sample. When high and low Ar pressure deposited Co films are associated in a single hard layer, the  $\text{Co}(5\text{nm})/\text{Co}^*(20\text{nm})$  bi-layer is anisotropic and has a medium coercive field. The soft anisotropic Co layer is exchange biased by a layer composed of low interacting grains which reversal occurs with the appearance of ripple type domain structure. As a result, magnetization reversal in the case of  $\text{Co}/\text{Co}^*$  occurs by nucleation and propagation of domains which is hindered. Finally, the magnetic properties of the hard layer can be tuned by changing  $e_{\text{Co}}$  in the  $\text{Co}(e_{\text{Co}} \text{ nm})/\text{Co}^*(20\text{nm})$  stack and when they are chosen to be anisotropic, the easy magnetization axis of the soft layer and hard bilayer are parallel.

## DISCUSSION

Tunnel magneto-resistance measurements have been shown to be highly sensitive to local magnetization fluctuations in the electrodes in contact with the barrier [5]. This sensitivity has been used in this study as a first step to predict the duplication of the hard layer domain structure template in the soft layer. Complete (—) and Minor(-•-, -o-) TMR loops are shown in figure 1 for a sample  $\text{Co}(10\text{nm})/\text{Al}(1.2 \text{ nm, ox } 30\text{s})/\text{Co}(5 \text{ nm})/\text{Co}^*(20\text{nm})$ . After saturation at 850 Oe, the applied field along the easy axis of the soft  $\text{Co}(10\text{nm})$  layer is decreased down to  $H_{\text{sat}} = -850 \text{ Oe}$  or  $H_{\text{rev}}$  and the step sequence is reversed in the positive field direction. When the field  $H$  is decreased down to  $H_{\text{sat}}$ , the TMR cycle is symmetric and holds two resistance jumps as presented in figure 1 (—). It reveals clearly two resistance states even if after the reversal of the soft Co layer at  $H_0$  a gradual increase of resistance is observed before the plateau. When  $H_{\text{rev}} = -100 \text{ Oe}$  (figure 1 (...)), the minor cycle appears to be shifted by a field of  $-17 \text{ Oe}$ , the ferromagnetic coupling field  $H_f$  existing between the two electrodes. When the field is decreased down to  $H_{\text{rev}}$  between  $-105$  and  $-125 \text{ Oe}$  and reversed again in the positive field direction, the resistance of the junction remains constant between  $H_{\text{rev}}$  and  $H_1$ . In the positive quadrant of the loop, three resistance jumps with different signs appear at some fields named  $H_1$ ,  $H_2$  and  $H_3$ . Particularly interesting is the fact that for applied fields between  $H_1$  and  $H_2$ , the resistance of the junction is close to the resistance measured when the magnetizations of the two magnetic electrodes are in a parallel configuration. Therefore, on each side of the barrier, the magnetizations are locally parallel even if the hard magnetic layer is far from magnetic saturation. As a consequence, the domain structure of the hard Co layer must be duplicated in the soft Co layer.



**Figure 1.** Complete (-) and minor (o,•, ...) magneto-resistance cycles measured on a  $\text{Co}(10\text{nm})/\text{Al}(1.2\text{nm,ox}30\text{s})/\text{Co}(5\text{nm})/\text{Co}^*(20\text{nm})$  tunnel junction.

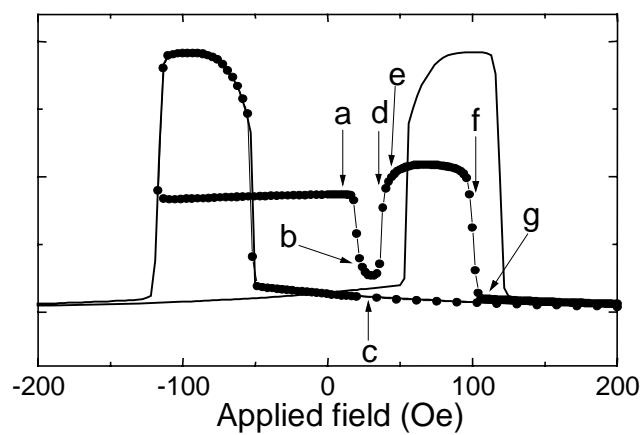


**Figure 2. (i) Kerr images a to g :** evolution of the domain structure measured by Kerr microscopy in the junction (upper part of each image, above the white line) and in the soft Co electrode (lower part of each image). The images a to e show the evolution around the duplication state.

**(ii) Kerr images (b-a) to (g-f) :** insight of the domain structure evolution is obtained from the difference of two successive Kerr images. The image (b-a) is obtained from the difference of images b and a. The white areas correspond to regions which have switched their magnetization.

**(iii) Magneto-resistance cycle :** field intensities corresponding to the Kerr images have been reported on this cycle.

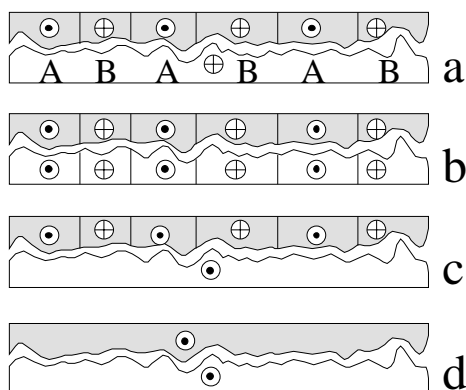
a: 25 Oe  
 b: 26 Oe  
 c: 32 Oe  
 d: 39 Oe  
 e: 41 Oe  
 f: 100 Oe



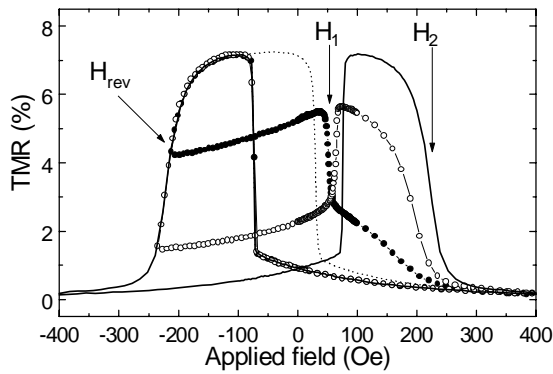
Kerr microscopy has been used to provide a direct proof of the domain duplication. Its depth sensitivity allows to visualize the evolution of the domain structure in the junction surface area for the two magnetic electrodes. The sample is first saturated by applying a magnetic field of +200 Oe. Then, it is decreased down to -120 Oe. With this field, the soft layer has totally switched (in the electrode and in the junction) and a domain structure appears in the hard layer. At this step, the applied field is increased in the positive direction and the domain structure remains unchanged up to +25 Oe. The domains which are oriented in the saturating field direction are bright while the domains which have switched appear with a dark contrast (figure 2a). By increasing the magnetic field, we can observe several changes in the Kerr images at some fields  $H_{1,2,3}$ , the same as given for figure 1.

From 25 Oe to 26 Oe, around  $H_1$ , an evolution of the contrast can be observed in the junction area since the bright domains become brighter. Indeed, figure 2 (b-a) confirms clearly that only these regions are affected. This change is due to the switch of the soft electrode magnetization in regions located over domains in the hard electrode with magnetization oriented in the positive saturating field direction. These regions, regions A in figure 3, are those which experience an effective local magnetic field equal to  $H + |H_f|$  where  $|H_f|$  is the local additional stray field due to the bright domains in the hard electrode. So, these regions switch at a field  $H_1$  whose value is lower than the intrinsic coercive field of the soft layer  $H_c$  (figure 3b). From 26 Oe to 32 Oe, no change of the domain structure in the junction could be observed while the magnetization of the soft electrode outside the junction has totally switched at  $H_c$ . From 32 Oe to 41 Oe, around  $H_2$ , the changes of the domain structure are confined to the dark regions of the junction which become brighter. This evolution depicted in figure 2 (d-c and e-d) is attributed to the reversal of regions in the soft electrode which have not switched at  $H_1$ . These regions, regions B in figure 3, are those which experience an effective local magnetic field equal to  $H - |H_f|$  where  $-|H_f|$  is the local additional stray field due to the dark domains in the hard electrode. So, these regions switch at a field  $H_2$  whose value is higher than  $H_c$  (figure 3c). Above 41 Oe, the main changes of contrast are easily attributed to the reversal of the hard layer.

Duplication of the domain structure relays on the distribution of magnetic coupling fields which can locally increase or decrease the applied field and so on the domain structure of the hard electrode. By reducing  $e_{C_0}$  to zero, magnetization reversal of the single  $Co^*$  layer occurs only by rotation and the magnetization cycle is fully isotropic in plane. Thus, the domain is completely different. Regions with main magnetization oriented in the negative direction do not coexist with regions with main magnetization oriented in the positive field direction. Instead, clockwise and counterclockwise rotations of neighboring magnetic grains lead to the appearance of  $360^\circ$  domain walls parallel to the external field axis.



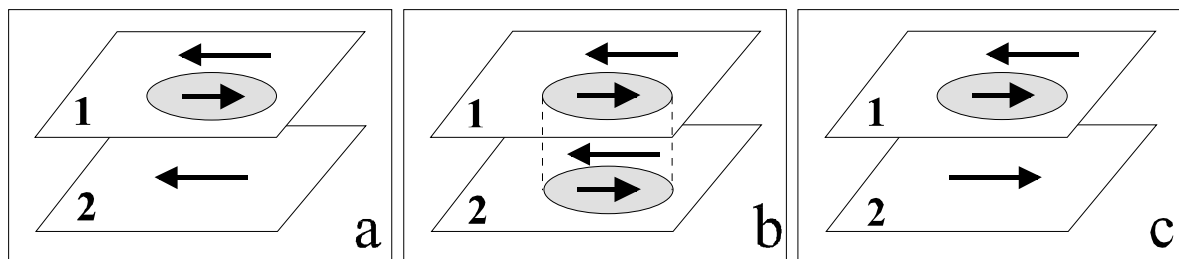
**Figure 3.** Sketch showing the evolution of the domain structure in each magnetic layer, the soft Co layer (bottom layer, white) and the hard Co/Co\* layer (top layer, gray scale). The symbols  $\odot$  and  $\otimes$  represent the main magnetization in each domain (oriented perpendicular to the paper sheet) respectively opposite and along the positive saturating field (applied along  $\odot$ ).



**Figure 4.** Complete (-) and minor (o,•, ....) magneto-resistance cycles measured on a Co(10nm)/Al(1.2nm,ox30s)/Co(5nm)/Co\*(20nm) tunnel junction.

The magnetization of each grain or of each region with extension less than the exchange correlation length points in the direction of the negative applied field. In fact, for a given value of  $H_{rev}$ , the cosine of the angle between the local magnetization and the applied field, and therefore the stray field parallel to the applied field, has the same sign all over the hard electrode volume. Then, all the regions of the Co soft electrode are submitted, along the external field axis, to the same effective field equal to  $H + H'_f$  since component of the stray field perpendicular to the applied field does not contribute for the reversal ( $H'_f$  is the ferromagnetic field coupling between the two electrodes). The value of  $H'_f$  increases from a negative value to a positive value when  $H_{rev}$  decreases as can be seen in figure 4. Indeed,  $H'_f$  follows a law similar to the cosine of the angle between the magnetization and the applied field at  $H_{rev}$ . This cosine law is also reflected in the shape of the TMR curve after reversal of the Co soft electrode. So, since the stray field of the hard layer domain structure along the applied field direction has the same sign all over the hard layer volume, no duplication could be observed.

To estimate the stability of the walls in each magnetic layer, we propose a simplified model sketched in figure 5. In this model, two magnetic layers are ferromagnetically coupled through a non magnetic layer, the magnetization of each layer is aligned with the applied field (either parallel or anti-parallel). We consider that non reversed domains exist in the hard layer which have a total surface area  $\Delta$ . The domain walls have a length or perimeter  $\lambda$ , an energy per unit surface area  $\sigma_1$  and no lateral extension. Let us call  $t_1$  and  $t_2$  the thicknesses of each magnetic layer,  $M_{s1}$  and  $M_{s2}$  the saturation magnetizations and  $J_F$  the interlayer coupling constant. When duplication occurs, the domains created in the soft layer 2 have a total surface area  $\Delta$  and domain walls have an energy per unit surface area equal to  $\sigma_2$ .



**Figure 5.** Three drawings showing the different magnetic configurations during the duplication process. In each box, the sheet 1 contains the magnetic configuration of the hard layer while the sheet 2 contains the one of the soft layer. The positive direction is oriented from the left to the right.

Comparing the energies of those different states, it appears that the magnetic state with a duplicated domain structure in layer 2 can exist if

$$J_F \geq \frac{\sigma_2 \lambda t_2}{4} \left[ \frac{1}{\Delta} + \frac{1}{S - \Delta} \right]$$

This equation is of particular importance because it shows that depending on the parameters of the hybrid multilayer stack, a minimum coupling strength is needed that duplication occurs. By changing the thickness of the alumina barrier, we can experimentally tune the strength of  $J_F$ . We have shown that in our samples, the minimum coupling field is around 6 Oe.

## CONCLUSIONS

In conclusion, we have studied the effect of the hard layer magnetic domain structure duplication in the soft layer in a magnetic tunnel junction. First evidence of the effect is given by the conventional tunnel transport measurements which interpretation has been confirmed using Kerr microscopy. It is shown that duplication occurs through the distribution of magnetic coupling fields which can locally increase or decrease the applied field. Indeed, removing those fluctuations by tuning the magnetic properties of the hard layer cancels the duplication. Finally, the influence of the hybrid multilayer stack parameters is discussed and a minimum coupling field of around 6 Oe is needed that duplication occurs in our tunnel junctions.

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