Tunnel magnetoresistance versus micromagnetism in magnetic tunnel junctions

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The impact of the micromagnetic configuration within the ferromagnetic layers on transport properties of hard/soft magnetic tunnel junctions is presented. An artificial ferrimagnetic (AFi) trilayer structure is used as a magnetically hard subsystem. Fluctuations in magnetization in the AFi affect the resistance of the tunnel junctions and are fully reflected in the shape and amplitude of the tunnel magnetoresistance signal. [S0021-8979(00)52908-9]

Quantum spin-dependent tunneling of electrons in magnetic tunnel junctions (MTJ) has attracted much attention since the discovery of large tunnel magnetoresistance (TMR) at room temperature.[1] However, up to now, much attention has been paid on tunnel barrier properties in detriment to magnetic properties of the MTJ electrodes and especially to their influence on the TMR signal. This article presents the correlation between micromagnetism and tunnel transport in Al_2O_3-based MTJ that use Co/Ru/Co or Co/Ru/$Co_{50}Fe_{50}$ artificial ferrimagnet (AFi) as a magnetically hard subsystem.[2,3] A magnetic force microscopy (MFM) study of the domain structure developed in the AFi shows the appearance of Néel type 360° walls during the net magnetic moment reversal. These walls have a deep impact on the magnetotransport properties of the MTJ. Indeed, the high sensitivity of the spin polarized tunneling in MTJ to local fluctuations of magnetization provides a precious tool to investigate the effect of a domain structure on the TMR signal at a macroscopic level. A sharp magnetization reversal of the soft subsystem ($Co_{50}Fe_{50}$/Fe), prevents a domain structure to persist in this bilayer away from its switching field. This homogeneously magnetized bilayer serves as a sensitive probe for small magnetic fluctuations associated with micromagnetic defects, domains and walls in the AFi magnetic layer adjacent to the barrier. These fluctuations affect the resistance of the MTJ and are fully reflected in the shape and amplitude of the TMR signal.

Reproducible characteristics of the magnetic layers have been achieved by first growing a Cr (1.6 nm)/Fe (6 nm)/Cu (30 nm) buffer layer on a previously sputter-etched 3 in. diam Si(111) wafer.[2] On the top of the buffer, the AFi trilayer Co (1.8 nm)/Ru (0.8 nm)/Co (3 nm) or Co (2 nm)/Ru (0.8 nm)/$Co_{50}Fe_{50}$ (3 nm) is stacked. The Al oxide barrier was formed by a rf Ar/O_2 plasma oxidation technique of a previously sputtered Al film. A magnetically soft bilayer (the so-called detection bilayer DL), sputtered on top of the Al oxide tunnel barrier, consists of $Co_{50}Fe_{50}$ (1 nm)/Fe (6 nm). This DL presents a square magnetization loop, with a coercive field smaller than 20 Oe and a magnetization reversal in a field range smaller than 2 Oe.[2] Therefore, for applied fields above 30 Oe, the DL can be considered as being in single domain state. The choice of $Co_{50}Fe_{50}$ (instead of pure Co), as magnetic layer in contact with the tunnel barrier (AFi or DL), is justified by its higher electron polarization ratio which is responsible in an enhancement of the TMR signal. As-deposited 3 in. wafers, containing the stack described above, were patterned by UV lithography into arrays of junctions with tunnel barrier surface areas ranging from 10×10 to $100\times100\,\mu m^2$. The junctions were measured at room temperature[2] using a conventional four-point technique.

Magnetic properties of as-deposited multilayer films were studied at both macroscopic and microscopic scales. Macroscopic magnetization curves were measured using an alternating gradient field magnetometer (AGFM) at room temperature. At a microscopic scale, the domain structure has been observed by MFM, in a tapping-lift phase-detection mode, in zero and in plane applied fields up to $|H| = 600$ Oe. $M-H$ and corresponding TMR loops [Fig. 1(a)], for a Co (2 nm)/Ru/CoFe (3 nm)/Al_2O_3/CoFe/Fe MTJ are measured in the antiferromagnetic (AF) plateau of the AFi,[2] where the magnetic moments of the AFi magnetic layers are in an AF configuration. In the positive part of the AF plateau [Fig. 1(a)], the magnetic layers adjacent to the barrier (DL and the thick topmost AFi layer) are parallel, being aligned along the positive field direction. In this parallel configuration, a high probability of tunneling induces a small resistance of the MTJ. By reversing the magnetic field, the DL reverses its magnetization, inducing an antiparallel configuration responsible for a high resistance of MTJ. This antiparallel state is preserved as long as the net magnetic moment of the AFi remains rigid and oriented along the positive field direction. As soon as the reversal of the net moment is com-

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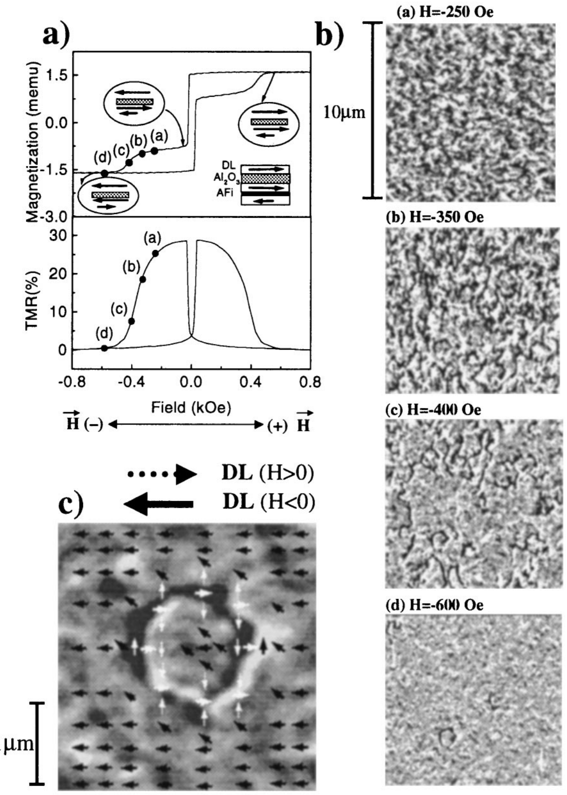

FIG. 1. (a) Magnetization and TMR curves of MTJ using different AFi configurations, when either (b) the thick or (c) the thin AFi magnetic layer is in contact with the AlO_x barrier. (d) Micromagnetic sketch of the magnetic configuration in the MTJ at some characteristic fields. In each panel, the direction of the detection bilayer (DL) and the external field are represented, as well as the distribution of magnetization within the thick and the thin magnetic layers of the AFi, illustrated by the top and bottom lines of arrows, respectively. The gray areas locate the center of the 360° Néel type wall in each of the layers.

pleted, the magnetization of the AFi topmost layer becomes again parallel with the DL, giving rise to a small resistance of the MTJ. Particularly important is that the antiparallel state does not give a flat plateau in the TMR curve. For fields higher than 250 Oe [Fig. 1(a)], the AFi starts to reverse its net magnetic moment, consequently it stops to behave as a fully magnetically homogeneous and rigid block.

Local MFM features are shown in Figs. 1(a)–1(d), in correlation with the TMR and $M-H$ curves [Fig. 1(a)]. The polycristalline Co and CoFe layers, constituted of small magnetic grains coupled by exchange interactions are macroscopically magnetically isotropic due to a random orientation of the easy magnetic axis of each grain. For the thickness range and weakly intergrain coupling involved in our samples,[3] the reversal of the layer magnetization proceeds mainly by individual grain magnetic moment rotation.[4] Reversing the magnetic field after positive saturation, moments inside areas presenting the smallest coupling (direct lateral exchange coupling and/or indirect AF interlayer coupling) start to rotate and drag in rotation the magnetization inside neighbor areas with stronger coupling. The sense of rotation is determined by a local effective anisotropy. 360° Néel domain walls will separate domains with magnetization rotating, during reversal, in antiphase (clockwise/anticlockwise). The evolution of the domain structure is presented in Fig. 1(b) that shows 360° walls appearing, increasing their effective length [Fig. 1(b) (a), (b)] and, for larger negative fields, gradually disappearing [Fig. 1(b) (c), (d)]. The micromagnetic configuration corresponding to a 360° wall,[5] shown in Fig. 1(c), is consistent with the measured MFM contrast.[3] The magnetic features are AF mirrored, by the strong interlayer AF coupling, in both magnetic layers of the AFi. This has a strong impact on the walls stability. The thick layer develops walls with centers opposite to the negative field direction. This situation is energetically unstable and, at a critical field, the wall in the thick film collapses. However, their stability is increased by the AF coupling with the mirrored walls in the thin layer which, having their center along the field direction, are very stable.[3] The AF coupling acts as an additional source of pinning, for the walls located in the thick layer up to fields for which the Zeeman energy overcomes the exchange.

The correlation between domain structure and magnetic field-dependent transport properties is done by defining an electric model for the conduction in MTJ. The model is based on two important aspects. First, since the tunnel current decreases exponentially with distance, the preferential conduction channels are the shortest paths across the insulator. Therefore, the magnitude of the tunnel current is determined by the local relative orientation of the ferromagnetic moments directly across the barrier. Second, the TMR signal depends only on the magnetic configuration of the layers in contact with the tunnel barrier. So, domains and domain walls give rise to conduction channels with different resistances determined by the lateral fluctuations of the angle between the magnetic moments of the magnetic layer in contact with the tunnel barrier. When the DL has a single domain configuration after switching (i.e., in our case for applied fields higher than 30 Oe) all features appearing in the TMR curves are due to domain walls or fluctuations in domain magnetization located in the AFi magnetic layer that is in contact with the tunnel barrier [shown by the MFM images in Figs. 1(b), (a)–(d)].

The in-cascade-resistances model has been used to explain two different magnetic histories, chosen to illustrate the different resistance channels linked to the presence of domain structure.

In the first case, the thick magnetic layer of the AFi is in contact with the tunnel barrier and therefore its magnetic behavior governs the shape and amplitude of the TMR signal. Related $M-H$ [Fig. 2(a)] and TMR curves [Fig. 2(b)] are measured on a Co (1.8 nm)/Ru (0.8 nm)/Co (3.0 nm)/Al_2O_3/CoFe (1 nm)/Fe (6 nm) MTJ. In the AF plateau of the AFi, magnetic layers are in a single domain state after positive field saturation [state (a) of Figs. 2(a), 2(b), and 2(d)]. By decreasing the positive applied field, uniformly magnetized regions appear, whose effective magnetic moments are aligned within a small angle bisected by the direction of the positive saturation field [Fig. 2(d), (b)]. These domains are separated by regions where the torque on the magnetic moments is zero defining the location of the emerging 360° walls. In negative field, after the switching of the DL, corresponding to a sharp increase of resistance [Figs. 2(b), (c) and

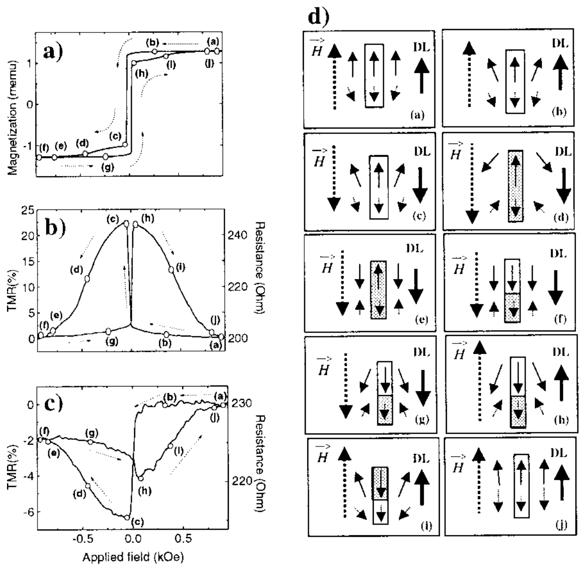

FIG. 2. (a) $M-H$ and corresponding TMR curve for Co/Ru/$Co_{50}Fe_{50}$/Al_2O_3/$Co_{50}Fe_{50}$/Fe MTJ, (b) MFM images, taken at at some significant magnetic fields, during the net AFi magnetic moment reversal. (c) Micromagnetic configuration of a circular 360° domain wall visualized by MFM.

2(d) (c)], the resistance decreases slowly. Indeed, the clockwise and counterclockwise rotation of the uniformly magnetized domains proceeds continuously and is mirrored in the thin magnetic layer by the AF coupling [Fig. 2(b) (d)]. As discussed above, the 360° walls, formed in the thick magnetic layer during its reversal, are unstable and disappear after completion of the topmost layer reversal [Fig. 2(d) (f)], while the 360° walls AF mirrored in the thin magnetic layer remain stable [Fig. 2(d) (e)] in the experimental field window ($|H|<1$ kOe). Since the thick magnetic layer is saturated in a negative applied field of $-H_{max}=-1$ kOe, the MR curve is symmetric.

The stability of the 360° walls in the thin AFi magnetic layer at negative applied fields of $-H_{max}=-1$ kOe is exemplified by the transport properties of Co (3 nm)/Ru (0.8 nm)/Co (1.8 nm)/Al_2O_3/CoFe (1 nm)/Fe (6 nm) MTJ [Fig. 2(c)], for which the field-dependent micromagnetic structure of topmost thin AFi layer governs the shape and amplitude of the TMR signal. Here again, the sample was firstly saturated in positive field and therefore all magnetic layers are in a single domain state [state (a) of Figs. 2(a), 2(c), and 2(d)]. In contrast to the previous case, the resistance of the MTJ is then maximum because of the antiparallel alignment between the magnetization of the DL and the thin magnetic layer [Fig. 2(d) (a)]. After the reversal of the DL, a sharp decrease of resistance occurs because of the parallel alignment of both layers adjacent to the barrier [Figs. 2(b) (c) and 2(d) (c)]. By further increasing the negative field, the resistance value increases slowly due to the clockwise-counterclockwise rotation of the uniformly magnetized domains in each magnetic layer of the AFi [Fig. 2(d) (d)]. The existence and stability of the 360° walls in the thin magnetic layer up to high negative fields is demonstrated on the TMR curves which never reach the high resistance state obtained in the positive saturated state [state (a)]. As shown in Figs. 2(d) (f) and 1(c) the walls act as low resistance channels, the direction of their center magnetization being oriented along the magnetization of the DL. By reducing the applied field, from $-H_{max}=-1$ kOe to zero, the rotation of the uniformly magnetized domains in each magnetic layer proceeds [Fig. 2(d) (g)] and the resistance slowly decreases. Here, the collection of parallel resistances is composed of high resistance channels (magnetization in domains nearly opposite to the magnetization of the DL) and by low resistance channels (360° walls have their center magnetization parallel to the DL magnetization) [Fig. 1(c)]. The MTJ resistance at zero field depends clearly on the density of walls which remained at $-H_{max}$ [Fig. 2(d) (g)]. In Figs. 2(c) (h) and 2(d) (h), the two networks of resistances are almost equivalent and therefore, the reversal of the DL gives rise to a small variation of the TMR signal. Then, the further increase of resistance is related to the rotation of the magnetization within the domains and the annihilation of the walls [Fig. 2(d) (j)].

The spin transport in MTJ is strongly dependent on the magnetic state of the two magnetic metal/oxide interfaces. When the magnetic hard subsystem (AFi) of the MTJ is in a multidomain configuration, the junction is modeled by a network of resistances in cascade, each resistance corresponds to a section in the junction containing a magnetic domain or a magnetic domain wall with a given local orientation relative to the detection bilayer. The TMR signal shape and amplitude are fully reflecting these fluctuations in magnetization (domains and domain walls), as well as their evolution in a magnetic field.

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