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Electric field-induced magnetoresistance in spin-valve/piezoelectric multiferroic laminates for low-power spintronics

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A B S T R A C T

Electric field-induced magnetic anisotropy has been realized in the spin-valve-based {$Ni_{80}Fe_{20}$/Cu/$Fe_{50}Co_{50}$/IrMn}/piezoelectric multiferroic laminates. In this system, electric-field control of magnetization is accomplished by strain mediated magnetoelectric coupling. Practically, the magnetization in the magnetostrictive FeCo layer of the spin-valve structure rotates under an effective compressive stress caused by the inverse piezoelectric effect in external electrical fields. This phenomenon is evidenced by the magnetization and magnetoresistance changes under the electrical field applied across the piezoelectric layer. The result shows great potential for advanced low-power spintronic devices.

1. Introduction

In the modern electronic and spintronic devices, the giant magnetoresistance (GMR) effect has been widely used in memory technologies and magnetic sensors. These devices however, function on the basis of the magnetic field-induced magnetization switching. In nanostructures, however, this physical mechanism is not efficient to control magnetic bits due to the large current. In particular, when approaching the downscaling limits (*e.g.* in densely packed arrays) the unavoidable distribution of writing parameters coupled to the large stray fields will lead to spreading program errors and may influence to neighborhood architectures. In this context, the current-induced (or spin-transfer driven) switching mode is considered to be more efficient. However, two main facts still remain challenging its applications in information storage technologies: firstly, all metal spintronic devices have low resistances and secondly, further reductions in the magnitude of the switching currents are still the subject of active researches [1]. In order to tackle these difficulties, electric (E) field-induced magnetization switching is a perspective solution and multiferroics consisting of ferromagnetic and ferroelectric orders have become an active research frontier [2–4].

GMR in the spin-valve structure is related to the spin depending scattering. In this structure, the resistance can be described by the relationship with the angle (θ) between the magnetization directions in the pinned and free ferromagnetic layers [1,5–7] as follows:

$$R(\theta) = R_P + ½(R_{AP} - R_P)(1 - \cos\theta) \quad (1)$$

here R_P and R_{AP} are low and high resistances of the spin-valve structure in parallel and antiparallel configurations, respectively.

The magnetization orientation, however, can also be influenced by an external strain thanks to the inverse magnetostriction (Villary effect) [7]. For the case of the positive magnetostriction, the magnetization is favored to align parallel to the tensile stress direction and perpendicular to the compressive stress direction. In this case, the stress sensing layer is preferred with a highly magnetostrictive material and the maximal change in the magnetization direction can reach up to 90°. Practically, the pressure sensors based on GMR and spin-valve structures were already proposed [5–7] and Refs. therein. Developing the principle of the above mentioned strain-driven magnetization rotation, E-field induced large magnetic anisotropy has been achieved in several multiferroic heterostructures via strain mediated magnetoelectric (ME) coupling [8–12]. MingLiu et al. [11] have investigated the E-field induced magnetization and magnetoresistance of the free (magnetostrictive) Co layer in the spin-valve based FeMn/$Ni_{80}Fe_{20}$/Cu/Co/PZN–PT multiferroic heterostructure, where the single crystal ferroelectric PZN–PT with different in-plane piezoelectric coefficients allows to clarify the role of corresponding in-plane strains. There, the coercivity and magnetoresistance enhancement of 100% and 3% were reported, respectively.

This paper deals with a power efficient E-field tunable magnetization realized in the spin-valve-based {IrMn/$Fe_{50}Co_{50}$/Cu/$Ni_{80}Fe_{20}$/Si}/PZT laminates. In this structure, only the pinned

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(magnetostrictive) $Fe_{50}Co_{50}$ layer serves as strain sensing layer. Thanks to the ME coupling between (ferro)magnetic (spin-valve) structure and piezoelectric (PZT) layers, the magnetization in the pinned FeCo layer can be turned under the mechanical strains caused by the inverse piezoelectric effect in an external *E*-field (or an external voltage). The $Ni_{80}Fe_{20}$ with a close-to-zero magnetostriction is chosen as the reference layer, which is almost not being influenced of internal stress. The PZT slabs under investigation, however, are polycrystal with equally distributed bi-axial strains. The objective of this study is to investigate the magnetization and magnetoresistance changes due to an effective stress induced by a voltage (V_{PZT}) applied across the PZT slab in proper longitudinal and transversal spin-valve configurations.

2. Experimental

The spin-valve {Ta(5 nm)/$Ni_{80}Fe_{20}$(10 nm)/Cu(1.2 nm)/$Fe_{50}Co_{50}$ (8 nm)/IrMn(15 nm)/Ta(5 nm)} structures were prepared using magnetron sputtering technique on 150 μm thick glass substrate under working pressure of 1 mTorr and the base pressure of 7×10^{-7} Torr. A uniform magnetic field of 400 Oe was applied parallel to the film plane during the sputtering process. This magnetic field induces a magnetic anisotropy in the ferromagnetic layers then aligns the pinning direction of the antiferromagnetic IrMn layer.

Spin-valve/PZT composites were manufactured by bonding the 2×12 mm^2 rectangular spin-valve films on the surface of a 12×12 mm^2 square piezoelectric slab (0.5 mm thick). The PZT (APCC-855) slab is out-of-plane polarized and supplied by American Piezoceramics Inc., PA, USA.

In this paper, two different (longitudinal and transversal) configurations corresponding to two different alignment of the pinning (easy) direction have been prepared: (*i*) along the length (Fig. 1a) and (*ii*) along the width (Fig. 1b) of the spin-valve rectangular structure, respectively. The magnetization and the magnetoresistance was measured in the magnetic fields applied parallel to the easy axis of spin-valve structure using VSM (Lake Shore 7400) and a collinear four-point probe methods, respectively. For the later measurement, the electric current $I_R=1$ mA is passed along the length of the spin-valve structure for sensing its resistance. The measurements were carried out in different external electric fields $E(=V_{PZT}/t_{PZT})$ up to 16 kV/cm (*i.e.* an electric voltage $V_{PZT}=800$ V) applied across the normal direction of the PZT slab.

3. Results and discussion

Shown in Fig. 2(a,b) are the full range in-plan magnetic hysteresis loops under zero and applied *E*-field of 12 kV/cm for the longitudinal and transversal spin-valve/PZT configurations, respectively. Sweeping the magnetic fields from positive to negative ones, the magnetization remains almost saturation in high positive magnetic fields.

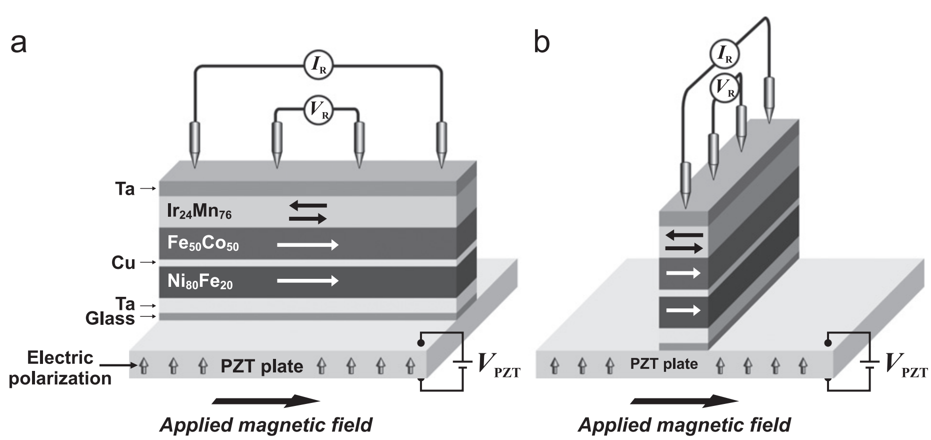

Fig. 1. Schematic spin-valve/PZT laminate configurations: the magnetic easy axis is parallel (a) and perpendicular (b) to the length of samples (named as longitudinal and transversal configurations, respectively).

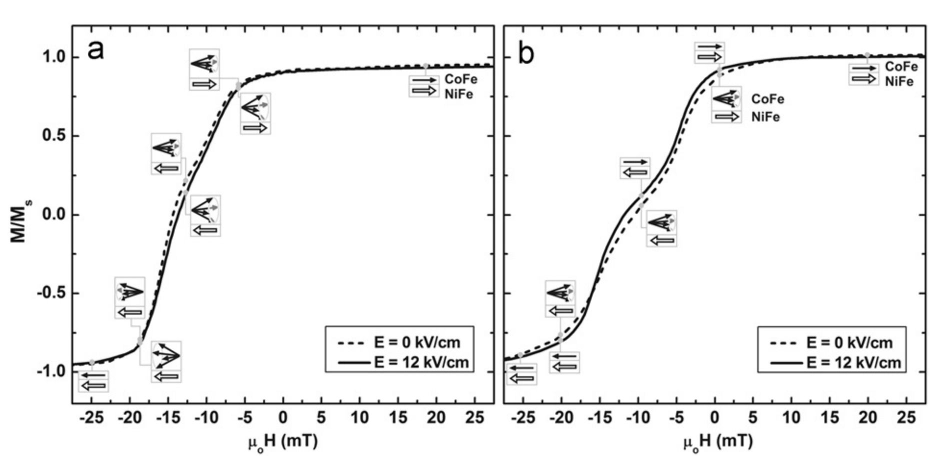

Fig. 2. Full range in-plan magnetic hysteresis loops under zero and applied *E*-field of 12 kV/cm for the longitudinal (a) and transversal (b) spin-valve/PZT configurations.