A room-temperature electrical field-controlled magnetic memory cell

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We present a method that allows changing the anisotropy and the magnetic characteristics of piezoelectric–ferromagnetic hybrid structures by electric fields, thereby suppressing the need for external or local magnetic fields. We have investigated the magnetic properties of single $\text{Co}_{50}\text{Fe}_{50}$ and $\text{CoFe}_{80}\text{B}_{20}$ magnetostrictive thin films as well as of high-quality bottom-pinned spin valves (SV) sputtered on piezoelectric substrates [lead zirconate titanate (PZT)] and patterned in an interdigitated transducer (IDT). Induction of a uniaxial anisotropy axis and the changes on coercivity and switching fields as a function of the applied bias voltage on the IDT are analyzed and interpreted. The down-scalability of this hybrid method supports the possibility of achieving low-power/low-voltage control of the switching fields and shows the feasibility of a hybrid ferroelectric magnetic memory cell.

I. INTRODUCTION

Magnetic random access memories (MRAMs) have been one of the most promising candidates for the realization of nonvolatile memory devices.¹ However, due to problems in localizing an external magnetic field on the magnetic cell itself to switch the relative direction of the spontaneous magnetization, alternatives to magnetic field induced switching such as thermal-assisted switching² and current-induced switching³ are currently being demonstrated in MRAM prototypes.

One alternative is the use of functional devices based on multiferroics, i.e., based on materials that can combine in just one material or system, two or more of the three ferroic properties: ferroelectricity, ferromagnetism, and ferroelasticity.⁴

Despite the enormous potentialities of single-multiferroic materials, it is still necessary to find a multiferroic with stronger ferroelectric and ferromagnetic parameters that are both retained at room temperature.⁵

One way to solve these limitations is to electrically control the magnetic properties, or vice versa, indirectly, i.e., by using hybrid systems based on multiferroics that make use of the ferroelasticity property. This can be achieved through the combination of magnetostrictive and piezoelectric materials.

We report herein significant electric field-induced changes on magnetic switching achieved through a hybrid system made of a piezoelectric substrate and a magnetostrictive thin film at room temperature.

II. EXPERIMENTAL

To achieve a functional device based on a multiferroic piezoelectric–ferromagnetic system, we used soft commercial piezoelectric ceramic substrates with high piezoelectric coefficients and deposited ferromagnetic thin films or multilayers, made from highly magnetostrictive materials such as $\text{Co}_{50}\text{Fe}_{50}$ and $\text{CoFe}_{80}\text{B}_{20}$, on top.^{6,7}

The piezoelectric ceramics used were provided by MorganElectroCeramics (Waldkraiburg, Germany), which had previously poled them using the available top and bottom electrodes. With this poling process, the ferroelectric domains were aligned along the poling field, giving rise to an electric polarization P perpendicular to the plane of the substrate. The electrodes used to pole the PZT plate were chemically removed, and the roughness of the top surface was reduced to 0.8-nm RMS (measured on a $5 \times 5 \mu\text{m}^2$ atomic force microscope scan) by a silica-based chemical–mechanical polishing step.

In most of the piezoelectric transducer applications up to now, the electric field is applied parallel to the polar axis of the piezoceramic to obtain displacements parallel and perpendicular to this axis, respectively. Experimental work has mainly focused on the increase of the corresponding piezocoefficients d_{33} and d_{31} and on the determination of the piezoelectric switching characteristics and origin of hysteresis, such as domain–wall motions.⁸

Little is known about the piezoelectric coefficient d_{15} related to the shear strain, which is induced when the electric field is applied perpendicular to the polar axis. In our case, the poling direction is along the z direction (imposed by the position of the initial electrodes) and the electric field is applied, in first order, along the y direction (imposed by the position of the new ferromagnetic

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electrodes). It is expected that, in this mode, the piezo-electric substrate would behave linearly at small electric field amplitudes, similar to the hard axis behavior in magnetic systems. At high electric fields, nonlinearity comes in and eventually can lead to a depoling or a poling along another direction. Electrical depoling is again related to irreversible changes of the domain configuration and limits the applicable electric field to ~ 10 kV/cm for the fairly soft PZT substrates that we are using.⁹ The d_{15} shear coefficient is 515×10^{-12} m/V, which is one of the highest values commercially available for PZTs with a processing-compatible Curie temperature above 280 °C.

The ferromagnetic films were deposited on the PZT and always capped with a 3-nm Ta layer by DC sputtering and patterned in an interdigitated transducer (IDT) shape through a lift-off process to obtain two sets of 8 fingers that generate uniaxial strain, both tensile and compressive, in the electrodes plane.

The electrical-field influence on the magnetic hysteresis loops was measured through the longitudinal magneto-optical Kerr effect (MOKE) and for spin valves, also through giant magneto resistance (GMR) measurements. In the MOKE measurements, the optical beam is focused on the middle of the IDT finger. In this case, the magnetic field is applied along the x direction, where different electric fields are applied across the two electrodes, resulting in strain perpendicular to the magnetic field. The GMR measurements were done using a four-point resistance technique with the current flowing along the length of the electrode (x axis) and the magnetic field applied along the x axis. Different electric fields were applied across the two sets of electrodes.

III. RESULTS AND DISCUSSION

A. Electric field-controlled hysteresis curves in single thin films and spin valves

Figure 1(a) shows how the $\text{Co}_{50}\text{Fe}_{50}$ thin-film hysteresis loop changes according to the applied electrical field along the electrodes. These changes can be explained through the magnetostrictive effect that is generally described by an anisotropy-like contribution to the total anisotropy energy term: $E_k = E_{\text{shape}} + E_{\text{crystalline}} - \frac{3}{2}\lambda\sigma \sin^2\theta$, where λ is the magnetostrictive coefficient, σ the stress amplitude, and θ the angle between the magnetization and the stress direction. For $\text{Co}_{50}\text{Fe}_{50}$, the reported λ is equal to 30×10^{-6} .⁶

Essentially, an extra uniaxial anisotropy field is induced in function of the applied electrical field. When a positive electric field of +10 kV/m is applied, which corresponds to a tensile stress, the magnetic domains tend to align along the stress axis, which decreases the squareness of the hysteresis loop. The opposite is seen when a negative electric field of -10 kV/m is applied,

FIG. 1. (a) $\text{Co}_{50}\text{Fe}_{50}$ 50-nm thin-film MOKE hysteresis loop area in function of the applied electrical field along the electrodes. (b) Hysteresis loop areas in function of the applied electrical field along the electrodes, for four different thicknesses of $\text{Co}_{50}\text{Fe}_{50}$: 5, 10, 20, and 50 nm.

which corresponds to a compressive stress. In this case, the magnetic domains tend to align perpendicularly to the stress axis, which increases the squareness of the hysteresis loop.

This experiment, shown in Fig. 1(b), was performed for different thicknesses of $\text{Co}_{50}\text{Fe}_{50}$, and area was plotted versus thickness. The relative area variations for the 50-nm-thick film are +14.4% and -16.4% when the positive (+10 kV/cm) and the negative (-10 kV/cm) electric field cases are compared with the zero electric field case (0 kV/cm), respectively. Note that, because the PZT itself has a small remanence in the coercive field when the electrical field is swept between +10 and -10 kV/cm, the area value considered for the zero electric field corresponds to an average. This value is obtained by averaging between the obtained zero electric field measurement after measuring a positive (+10 kV/cm) and a negative (-10 kV/cm) electrical field.¹⁰

The same effect is also visible in more complex structures, such as spin valves [Ta(3.5)/Py(2)/IrMn(6)/ $\text{Co}_{50}\text{Fe}_{50}$ (3.5)/Cu(2.7)/ $\text{Co}_{50}\text{Fe}_{50}$ (3)/Ta(3.5), all dimensions in nm]. The hysteresis curve area variation for

the free layers of this spin valve is calculated from a MOKE measurement that is only sensitive to the top $\text{Co}_{50}\text{Fe}_{50}$ layer and is +20% and -22% when the positive (+10 kV/cm) and negative (-10 kV/cm) fields are compared with the zero field (0 kV/cm), respectively.

A full GMR loop, shown in Fig. 2(b), indicates first that the IrMn exchange bias field is not affected, despite the visible changes verified on the spin-valve free and pinned layers due to elastic strain on the spin valve.

For both single thin films and spin valves, it is possible to verify a common trend, i.e., in function of the applied electrical field, an easy/hard axis is induced by the stress (hard axis for a negative electric field and easy axis for a positive electric field in case of a positive magnetostrictive coefficient).

B. Electrical switching without external magnetic fields

To show the possibility of switching without the use of external magnetic fields, we have measured, reproducibly, the spin-valve resistance changes during function of an applied electric field along the electrodes at zero magnetic fields.

FIG. 2. (a) MOKE and (b) GMR spin-valve loop variation as a function of the applied electric field along the electrodes [Ta(3.5)/Py(2)/IrMn(6)/ $\text{Co}_{50}\text{Fe}_{50}$ (3.5)/Cu(2.7)/ $\text{Co}_{50}\text{Fe}_{50}$ (3)/Ta(3.5), all dimensions in nm].

FIG. 3. Spin-valve resistance change as a function of the applied electric field along the electrodes at zero magnetic field.

As seen in Fig. 3, it is possible to have two different resistance states, according to the applied electric field. The higher the electrical field applied on the electrodes, the larger the difference in resistance in between the two states. However, because the maximal observed differences are on the order of a few hundred micro-ohms, this method is inefficient. This change in resistance merely corresponds to a difference in the angle θ between the free and the pinned layers. Moreover, when the electrical field is removed, the system relaxes back to its initial axis, and nonvolatility cannot be guaranteed with this method.

C. Electrical-assisted switching with electrical magnetic field

Because switching without external magnetic fields of the used IDT structures is not feasible, we performed a similar study using a fixed external magnetic field smaller than the spin-valve free layer switching field, which is -8 kA/m.

An experiment was performed in which the consecutive stages are numbered in Figs. 4(a) and 4(b).

Stage 1: Magnetic field of +15 kA/m is applied along the easy axis while at the same time an electric field of +10 kV/m (+200 V) is applied on the electrodes to magnetically initialize the system in a low-resistance state, R_p , that corresponds to the parallel alignment of the spin-valve free and pinned layers.

Stage 2: Applied electric field was maintained constant, and the applied magnetic field was changed to a value below the switching field of the spin valve (-6 kA/m), resulting in a slight increase in resistance.

Stage 3: External magnetic field was held fixed, and the applied electric field was changed from +10 to -10 kV/m (+200 to -200 V), resulting in a switching of the spin valve to a high-resistance state of ~50% of the total magnetoresistance (MR) value, defined as $MR = R_p - R_{ap}/R_p$, where R_p and R_{ap} are the resistances for the parallel and antiparallel configurations, respectively.

FIG. 4. (a) Spin-valve resistance change as a function of the applied electric and external magnetic fields along the electrodes. (b) Indication, on the spin-valve MOKE loop, of the principal stages measured during the experiment.

Stage 4: Still with a fixed magnetic field, the applied electric field was switched back to +10 kV/m, which resulted in a further increase of resistance to ~80% of the total magnetoresistance. We anticipate that, in this case, we have performed a switch of the free layer.

Stage 5: The applied electric field was changed from +10 to -10 kV/m to verify the reliability of the effect on the switching.

Stage 6: The applied magnetic field was increased to -15 kA/m to obtain complete magnetic saturation and to reinitialize the system into an antiparallel state.

Stage 7: The applied electric field was maintained constant, and the applied magnetic field was changed to a value below the switching field of the spin valve (2 kA/m), resulting in a slight decrease in resistance.

Stage 8: The external magnetic field was held fixed, and the applied electric field was changed from +10 to -10 kV/m (+200 to -200 V), resulting again in a switching of the spin valve to a high-resistance state of ~50% of the total MR value.

Stage 9: The magnetic field was still held fixed, and the applied electric field was switched back to +10 kV/m, which resulted in a further reduction of resistance to ~80% of the total magnetoresistance.

Stage 10: The applied electric field was changed from +10 to -10 kV/m to verify the reliability of the effect on the switching.

Stage 11: After the applied magnetic field was increased to 15 kV/m, the system returned to its initial position, Stage 1.

We have thus shown that it is possible to achieve an electrical field assisted magnetic switching of the free layer of a spin valve. This method allows reducing the switching field of the spin valve by, approximately, 25%.

D. Scaling down

As the first step in demonstrating the possibility of having a low-power/low-voltage method, we have down-scaled the 50 nm $\text{Co}_{50}\text{Fe}_{50}$ IDT structure, with fingers 3 mm long $\times$ 200 μm wide, 2, 4, 10, and 20 times. The maximum used electric field for all cases was 10 kV/cm, i.e., 100 V was applied to 100- μm electrodes separated by 100 μm , 50 V was applied to 50- μm electrodes separated by 50 μm , 20 V was applied to 20 μm electrodes separated by 20 μm , and finally 10 V was applied to 10- μm electrodes separated by 10 μm .

As shown in Fig. 5, the electric field-induced effects on the IDT magnetic properties do not change considerably in function of the dimensions. This suggests that scaling down further might allow developing a way to have a low-power/low-voltage switching field control of individual MRAM cells or the sensitivity of miniaturized magnetoresistive sensors, i.e., submicron structures will be switchable by voltages <0.5 V.

E. Alternative magnetostrictive material

Because $\text{CoFe}_{80}\text{B}_{20}$ is also a magnetostrictive material that is reported to have a high magnetostrictive coefficient, $\lambda = 31 \times 10^{-6}$,⁷ we have repeated the same magneto-optical studies for single $\text{CoFe}_{80}\text{B}_{20}$ layers. As seen in Fig. 6(a), this effect is about twice as high for $\text{CoFe}_{80}\text{B}_{20}$ thin films as for $\text{Co}_{50}\text{Fe}_{50}$. This is most

FIG. 5. $\text{Co}_{50}\text{Fe}_{50}$ 50-nm thin-film magnetic property as a function of the applied electric field along the electrodes when scaling down the IDT.

FIG. 6. (a) Hysteresis loop area as a function of the applied electrical field along the electrodes, for four different thicknesses of CoFe₈₀B₂₀: 5, 10, 20, and 50 nm. (b) CoFe₈₀B₂₀ 50-nm thin-film MOKE hysteresis loop area as a function of the applied electrical field along the electrodes.

evident for the 50-nm-thick film, shown in Fig. 6(b), where the hysteresis area variations as functions of the applied electric field are +40.1% and -43.6%, respectively. Remember that, when the same conditions were used for Co₅₀Fe₅₀, the obtained variations were +14.4% and -16.4%.

CoFe₈₀B₂₀ is currently an important material for MgO-based tunnel junctions. Essentially, to achieve higher tunnel magnetoresistance (TMR) values in these junctions, it is necessary to anneal them at ~400 °C in high magnetic fields to crystallize the CoFe₈₀B₂₀ from an amorphous state.¹¹ Because the CoFe₈₀B₂₀ used in our IDT structures is expected to be amorphous, this suggests that the verified changes in coercivity and MR in function of the applied electrical field should increase even further after crystallization of CoFe₈₀B₂₀ through annealing.

IV. CONCLUSION

We have shown that it is possible, in a reproducible way, to electrically control the hysteresis curves for functional devices based on multiferroics made of single magnetostrictive layers (CoFe₈₀B₂₀ and Co₅₀Fe₅₀) or spin valves deposited on PZT.

For these IDT structures, it was shown that it is possible

to have reliable and reproducible electrical field-induced switching close to the magnetic switching field.

Scaling down this hybrid structure indicates that it should be possible to achieve a low-voltage/low-power control of magnetic reversal fields in thin ferromagnetic structures.

Future investigations will concentrate on CoFe₈₀B₂₀, a highly magnetostrictive material widely used in magnetic memories.

Finally, it is expected that these results will lead to new voltage-tunable ferromagnetic devices beyond magnetic memories, such as sensors with tunable range and sensitivity and tunable frequency RF components.

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REFERENCES

1. S.S.P. Parkin, K.P. Roche, M.G. Samant, P.M. Rice, R.B. Beyers, E.J. O'Sullivan, S.L. Brown, J. Bucchigano, D.W. Abraham, M.Y.L. Rooks, P.L. Trouilloud, R.A. Wanner, and W.J. Gallagher: Exchange-biased magnetic tunnel junctions and application to nonvolatile magnetic random-access memory (invited). *J. Appl. Phys.* **85**, 5828 (1999).
2. M. Kerekes, R.C. Sousa, I.L. Prejbeanu, O. Redon, U. Ebels, C. Baraduc, B. Dieny, J.-P. Nozières, P.P. Freitas, and P. Xavier: Dynamic heating in submicron size magnetic tunnel junctions with exchange biased storage layer. *J. Appl. Phys.* **97**, 10P501 (2005).
3. E.B. Myers, D.C. Ralph, J.A. Katine, R.N. Louie, and R.A. Buhrman: Current-induced switching of domains in magnetic multilayer devices. *Science* **285**, 867 (1999).
4. N.A. Spaldin and M. Fiebig: The renaissance of magnetoelectric multiferroics. *Science* **309**, 391 (2005).
5. W. Eerenstein, N.D. Mathur, and J.F. Scott: Multiferroic and magnetoelectric materials. *Nature* **442**, 759 (2006).
6. K. Adachi, D. Bonnenberg, J.J.M. Franse, R. Gersdorf, K.A. Hempel, K. Kanematsu, S. Misawa, M. Shiga, M.B. Stearns, and H.P.J. Wijn: *Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology—New Series: Group 3*, Vol. 19, (Springer-Verlag, Berlin, and Heidelberg GmbH & Co. K, 1986), p. 225.
7. D. Wang, C. Nordman, Z. Qian, J.M. Daughton, and J. Myers: Magnetostriction effect of amorphous CoFeB thin films and application in spin-dependent tunnel junctions. *J. Appl. Phys.* **97**, 10C906 (2005).
8. S.J. Gross, S. Tadigadapa, T.N. Jackson, S. Trolier-McKinstry, and Q.Q. Zhang: Lead-zirconate-titanate-based piezoelectric micromachined switch. *Appl. Phys. Lett.* **83**, 174 (2003).
9. V. Mueller and Q.M. Zhang: Shear response of lead zirconate titanate piezoceramics. *J. Appl. Phys.* **83**, 3754 (1998).
10. H. Boukari, C. Cavaco, W. Eyckmans, L. Lagae, and G. Borghs: Voltage assisted magnetic switching in Co₅₀Fe₅₀ interdigitated electrodes. *J. Appl. Phys.* **101**, 054903 (2007).
11. J. Hayakawa, S. Ikeda, Y.M. Lee, F. Matsukura, and H. Ohno: Effect of high annealing temperature on giant tunnel magnetoresistance ratio of CoFeB/MgO/CoFeB magnetic tunnel junction. *Appl. Phys. Lett.* **89**, 232510 (2006).