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Citation: Appl. Phys. Lett. **99**, 192507 (2011); doi: 10.1063/1.3660259
View online: http://dx.doi.org/10.1063/1.3660259
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v99/i19
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Room temperature magnetoelectric memory cell using stress-mediated magnetoelastic switching in nanostructured multilayers

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(Received 5 July 2011; accepted 23 October 2011; published online 9 November 2011)

We present here the demonstration of magnetoelectric switching of magnetization between two stable positions defined by a combination of anisotropy and magnetic field. A magnetoelastic nanostructured multilayer with the required uni-axial characteristic was deposited onto a commercial piezoelectric actuator. Thanks to the inverse magnetostrictive effect, the effective anisotropy of the magnetic element is controlled by the applied voltage and used to switch magnetization from one state to the other. Both vibrating sample magnetometer and magneto-optical Kerr effect measurements have been performed and demonstrate the magnetoelectric switching. © *2011 American Institute of Physics*. [doi:10.1063/1.3660259]

The use of multiferroic or magnetoelectric (ME) materials possessing both a ferroelectric and a ferromagnetic phase coupled together[1] is of tremendous interest for non-volatile low power memory applications: only a very low energy is required to electrically write the information that can be subsequently read via the magnetic system without destroying it. Several approaches are considered in the literature: The inclusion of intrinsic multiferroic barriers into magnetic tunneling junctions (MTJ) allowed the implementation of a memory cell but still far below room temperature.[2] Also at very low temperatures, Chiba *et al*. reported direct control of magnetization by electric field in GaMnAs semiconductors.[3] For practical applications, the weak properties of room temperature multiferroics can be amplified using interfacial properties in order to control the value of an exchange field.[4,5] Besides intrinsic multiferroics, a solution is to mechanically couple magnetic and ferroelectric materials. A few recent works[6–9] relate the effect of stress on the magnetic properties of some magnetoelastic materials: piezoelectric stress can then be used to write magnetic information. It has also been reported that ME effect can also be used to read information stored in the form of different stress states.[10] Among these approaches, room temperature memory cells with simple switching procedures have hardly been shown. In the present letter, we focus on the demonstration of the writing of information in a stress-mediated magnetoelectric memory cell (MELRAM), working at room temperature. The concept of the cell is the following:[11] Information is written by the application of a voltage on the electrodes that lead to an electric field in the piezoelectric medium, which in turn generates stress on a monodomain magnetoelastic element. Depending on the sign of the voltage, the stress can change the anisotropy axis direction and thus cause the switching of magnetization between two equilibrium positions defined by a combination of magnetic anisotropy and polarizing magnetic field.[12,13] The reading of the information can be done using well known techniques such as giant magneto-resistance (GMR), magneto-resistance in MTJ, Hall effect, or so. Details are given below.

Figure 1 shows a schematic view of the device as well as the actual prototype. The stress is generated by a commercial piezoelectric stack actuator from *Piezomechanik Gmbh*. Application of a positive voltage on leads provokes an extension along the X axis, whereas negative voltage induces a compression. Before further processing, one side of the actuator was mechanically polished. The magnetic element is a $15 \times (TbCo_{2(5\mathrm{nm})}/FeCo_{(5\mathrm{nm})})$ exchange coupled multilayer. This type of structure is used as it combines a fairly high magnetostriction and a well defined uni-axial anisotropy. The film was deposited onto the polished side of the actuator through a shadow mask by RF sputtering using a rotary turn table in a Leybold Z550 equipment. The deposition was made under a magnetic field generated by permanent magnets in order to induce a magnetic easy axis (EA) in the desired direction, i.e., with an angle of 45° with respect to the X axis. The obtained film magnetization was characterized with a vibrating sample magnetometer (VSM). The magnetostriction was measured by laser deflectometry with the clamped beam technique. The deposited film has a saturation magnetization of $6 \times 10^5\,\mathrm{Am^{-1}}$ and an equivalent anisotropy field H_A of $1.45 \times 10^5\,\mathrm{Am^{-1}}$. The saturation magnetostriction λ_S is of about 10^{-4} and its Young's modulus is about 80 GPa.

In order to understand the principle of operation of the device, one can consider the magnetic free energy of the layer with the conventions of Figure 2. Assuming that the piezoelectric actuator only generates stress in the OX direction, the energy can be written as the sum of Zeeman, anisotropy, and magnetoelastic energy

$$F = V[-\mu_0 M H_s \cos(\phi) - \frac{1}{2}\mu_0 M H_A \sin^2(\phi) + \frac{3}{4}\lambda_S \sigma_{xx} \sin(2\phi)], \quad (1)$$

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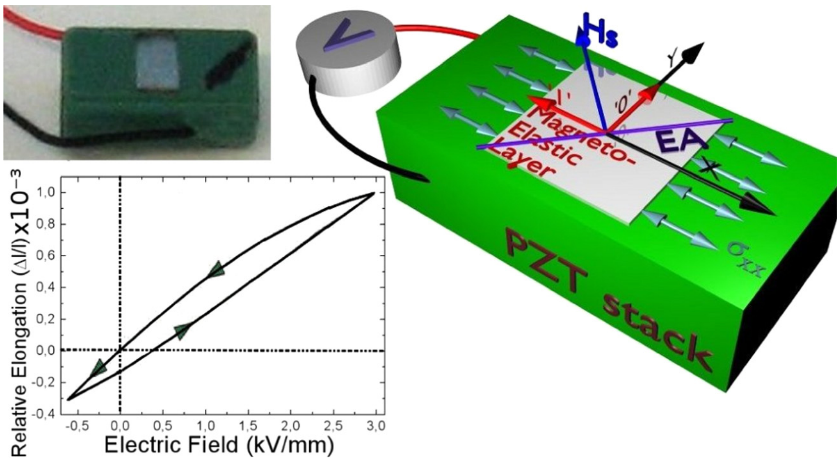

FIG. 1. (Color online) Schematic of the prototype and realized device and relative elongation cycle of the piezoelectric actuator as given by the provider.

where V is the volume of the element, M is the magnetization of the element, making an angle φ with respect to the hard axis (HA), H_S is a polarizing field applied in the hard axis direction, H_A is the value of the effective anisotropy field, σ_{xx} is the mechanical stresses applied to the element along the OX axis. The polarizing field H_S has a value of about $\sqrt{2}/2$ times the value of H_A. This way, two equilibrium positions are defined for the magnetization. This can be seen in Fig. 3 where the energy is displayed as a function of φ. At rest ($\sigma_{xx} = 0$), two minima of energy are found along the OY+ and OX− axis. When applying a positive voltage, a positive stress is generated, thus removing the energy barrier between the two states and favoring the energy minimum at $\varphi = +45°$. For a negative voltage, the stress is negative, and the favored minimum is $\varphi = -45°$. When removing the voltage, the energy barrier is restored, ensuring the stability in the new state.

In order to verify the switching operation, two types of measurements were performed at room temperature using a VSM as well as magneto optical Kerr effect (MOKE). In the first experiment, the vector VSM allowed to apply the polarizing field H_S in the hard axis direction while measuring the component of the magnetization along the easy axis, namely $M \times \sin(\varphi)$. The electric field inside the piezoelectric actuator is set by applying voltage on the leads. A measurement sequence is presented in Fig. 4: A positive or negative electric field is applied and subsequently removed. The electric field values are set by the operating range characteristics of the actuator, i.e., from −0.7 to 3 kV/mm. The expected relative elongation is given by the maker in Figure 1. With a 80 GPa Young's modulus for the magnetic layer, it can then be estimated that the stress range is $-24\,\text{MPa} < \sigma_{xx} < 80\,\text{MPa}$. Upon a positive electric field, the magnetization switches in the "1" state, whichever its previous state was, whereas upon negative values, it switches to the "0" state, whichever the previous state. It offers the advantage that knowing the previous state of the magnetization is not required as in "toggle" memory cells. Upon removal of the electric field, the new position is kept. As the information is stored by the magnetic system in one of the two defined states, it is to be noted that the slight hysteresis of the used piezo actuator has no significant influence on the switching process.

Since the principle of VSM measurement is inherently slow, another sample has been prepared with a smoother surface in order to be able to perform MOKE measurements. Fig. 5 represents a signal proportional to the magnetization component along the hard axis together with the applied electric field. This time, 10 ms pulses with a 1 ms rise time are applied. As in the first experiment, it can be seen that a positive pulse will result in the switching to the "1" state, and a negative will have M to switch to "0". Zooming on a switching point, it seems that the switching time is significantly longer that the pulse time, but this is believed to be a limitation of the experimental MOKE setup. In order to assess the switching speed of future devices, dynamic simulations have been performed using macrospin models as well as with the micromagnetic simulation software MAGPAR.[14]

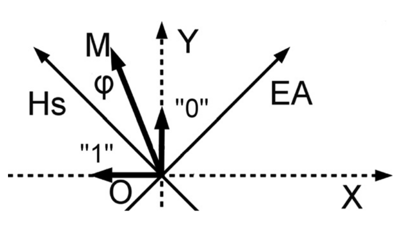

FIG. 2. Magnetic configuration: the magnetic element has a magnetic easy direction in the 45° direction. A polarizing field H_S is applied perpendicularly to this axis.

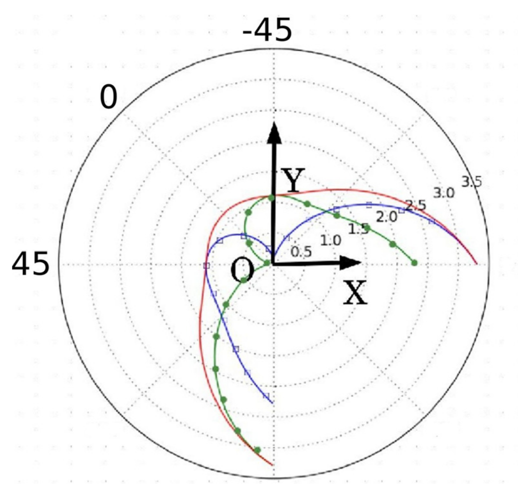

FIG. 3. (Color online) Magnetic free energy profiles (arb. units) of the system as a function of the magnetization angle for 3 stress states. Red-plain: no stress: two stable positions are defined for −45° and 45°. Blue-hollow squares: Compressive stress along OX → anisotropy along OY, only the −45° position is stable. Green-full circles: tensile stress along OX → anisotropy along OX, only the 45° position is stable.

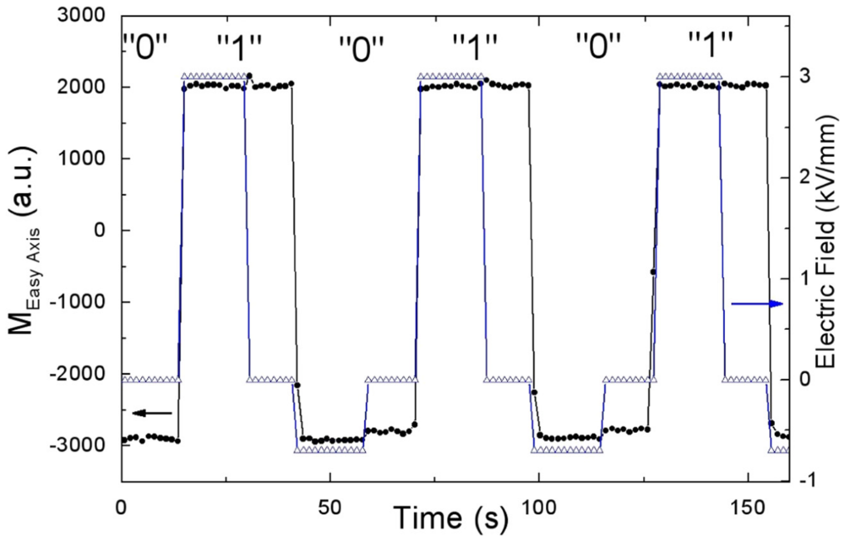

FIG. 4. (Color online) VSM measurements of the magnetization component along the easy axis. A positive electric field switches M in the "1" state and a negative field into the "0" state. The state is kept upon removal of the electric field.

Both confirmed that in a 100 nm long magnetoelastic elliptical element submitted to piezoelectric stress, the switching between the two defined equilibrium positions occurs in the nanosecond range. A continuum theory model for the nanoscale devices has also been developed in order to analyze thoroughly the coupling between the electric and elastic fields within the proposed structure.[15] It is able to determine the behaviour of the energy profile minima such as in Figure 3 as a function of the applied voltage and materials properties.

We have validated here the concept of a magnetoelectric memory cell operated via the effect of stress on anisotropy combined with the definition of 2 perpendicular stable positions in a uni-axial magnetoelastic element. A positive voltage sets the magnetization in one of the stable positions, whereas a negative voltage sets it in the other position. The position is kept when no voltage is applied. Since the information is stored magnetically, the readout can be made using magnetoresistive techniques. Simulations published elsewhere[11] confirm that the properties of existing materials are compatible with the realization of such a device at the nanometric scale. With the reduction of size, one can expect densities up to 40 Gbits cm^{-2} per layer, low energy, non-volatile memories. Given the very low expected power, such a device is a strong contender for vertical integration of several layers, quickly increasing the memory density.[16]

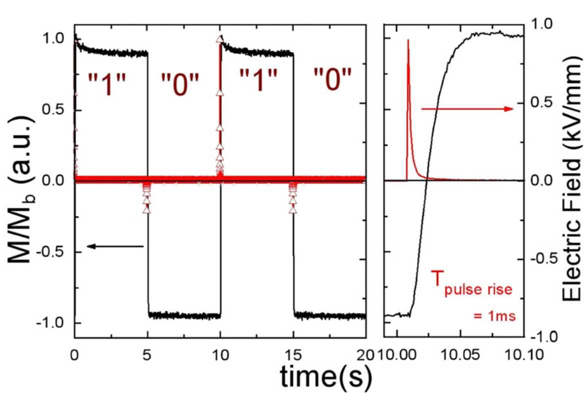

FIG. 5. (Color online) MOKE measurement of the magnetic element magnetization: a negative pulse voltage switches M in the "0" state and a positive pulse into the "1" state. Left: sequence over 20 s. Right: zoom around t = 10 s.

The authors would like to thank the Direction Gnrale de l'Armement (DGA-France) for the Ph.D. funding of Mr Y. Dusch. Part of this work is supported by the PRES Lille Nord de France as well as the PNano program of the french Agence Nationale de la Recherche (ANR)

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