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Stress-mediated magnetoelectric memory effect with uni-axial TbCo$_2$/FeCo multilayer on 011-cut PMN-PT ferroelectric relaxor

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We present here the implementation of a magnetoelectric memory with a voltage driven writing method using a ferroelectric relaxor substrate. The memory point consists of a magnetoelectric element in which two orthogonal stable magnetic states are defined by combining uni-axial anisotropy together with a magnetic polarization in the hard axis direction. Using a ferroelectric relaxor substrate, an anisotropic stress is created in the magnetic element when applying a voltage across electrodes. Because of 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. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4795440]

I. INTRODUCTION

As the need for energy efficient data processing and data storage booms, magneto-electric memories have raised a tremendous interest among research teams. They could indeed combine the advantages of magnetic storage, such as non-volatility, speed, and endurance, with energy efficient electric writing techniques. Intrinsic magnetoelectric materials (with the notable examples of Cr$_2$O$_3$ and BiFeO$_3$) have been considered in several designs, but offer only a weak magnetoelectric response at room temperature and therefore require either cryogenic techniques or precise control of the operating temperature. On the other hand, composite materials, introduced by Boomgaard et al. in 1976, use strain-coupled piezoelectric and magnetostrictive materials. They can operate at room temperature and offer several design possibilities. With such an interface strain coupling, electric field control of ferromagnetism was shown in iron thin film structures. Most of the composite memory devices proposed up to now are toggle memories, whose initial state must be known prior to writing operation, or involve complex schemes to switch between multiple anisotropy directions defined by crystallographic axes of epitaxially grown materials, or precisely synchronized driving signals.

In 2010, we proposed and patented an innovative memory device called MELRAM (Magnetoe-Electric Random Access Memory) based on a composite structure composed of a nanometer sized magnetostrictive material embedded in a piezoelectric matrix. In particular, we showed that the competition between an external magnetic field and uni-axial magnetic anisotropy can be used to define two perpendicular equilibrium positions for magnetization and that the application of stress can trigger the switch between both positions in a deterministic fashion. A macroscopic device using a commercial piezoelectric stack provided an experimental proof of concept of this memory element and demonstrated the writing principle using piezoelectric stress. The characterization of the magnetic state was performed using either a Vibrating Sample Magnetometer (VSM) or Magneto Optical Kerr Effect (MOKE). However, this approach is not suitable for an integrated device at the sub-micrometer scale. We hereby present the results obtained using a relaxor substrate with adequate symmetry and characteristics. Such a substrate has already been coupled to magnetic layers for memory applications by Wu et al. In their model, the information is supposed to be stored in the ferroelectric subsystem due to switchable remanent stress states. In our experiment, the information is stored in the magnetic subsystem and persists without either electrical tension or remanent stress.

II. PRINCIPLE OF THE MEMORY AND CONSIDERATIONS ABOUT STRESS

The magnetic and mechanical configurations of a MELRAM cell are given in Figure 1 and consist of a magnetic element with a defined easy axis (EA) at a 45° angle relative to the X axis, subjected to a polarizing field $H_2$ in the hard axis (HA) direction and a mechanical stress. The EA can be obtained by considering an ellipsoid shaped element or induced during the film preparation (e.g., sputtering under magnetic field). The element has a high magnetostriction $\lambda_S$. Assuming the magnetization is homogeneous in the film, the magnetic free energy of the system submitted to in-plane stress is described by the following equation:

$$F_{mag} = -M_H \cos\left(\frac{3\pi}{4} - \varphi\right) - \frac{1}{2} M_H \cos^2\left(\frac{\pi}{4} - \varphi\right) - \frac{3}{2} \lambda_S (\sigma_{xx} - \sigma_{yy}) \cos^2(\varphi) - \frac{3}{2} \lambda_S \sigma_{xy} \cos(\varphi) \sin(\varphi),$$

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Switching the magnetization to positions “1” or “0” means the energy profile is deformed by the magnetoelastic terms. Therefore, the last term of the energy has no contribution along the OX direction and the two stable positions marked “1” and “0” are aligned along the OX− and OY+ axes. When a stress is applied, the energy profile is deformed by the magnetoelastic terms. Switching the magnetization to positions “1” or “0” means favoring a minimum of energy for φ = π or φ = π/2, respectively. Therefore, the last term of the energy has no influence, since the product \( \cos(\varphi)\sin(\varphi) \) is zero in these two positions. Shear stress, thus, have to be avoided. However, the term in \( K \cdot \cos^2(\varphi) \) is of interest: depending on the sign and strength of \( K \), the energy profile is suitably modified. It can be also deduced that for a maximum efficiency, \( \sigma_{xx} \) and \( \sigma_{yy} \) have to be of opposite signs, which leads to conditions on the substrate properties. A first approach is to consider a piezoelectric material with an in-plane polarization and electrodes on opposite vertical sides in order to generate an in-plane electric field, as proposed, for instance, by Hu et al. The stress is then generated, say along OX using the \( d_{33} \) piezoelectric coefficient, and due to the Poisson effect, an opposite stress along OY is created. Unfortunately, this approach is limited to non-conductive magnetic layers as a conductive film induces a strong distortion of the electric field lines, which have to be perpendicular to the conductor, and therefore leads to improper stress generation. In this case, the electric polarization of the electroactive material has, then, to be perpendicular to the plane, and the relevant stress is related to the \( d_{31} \) and \( d_{32} \) coefficients. For most piezoelectrics, such as PZT, the deformation is isotropic in the plane and those coefficients are equal, leading to no effect on the magnetoelastic system. Suitable materials belong to a class of relaxors such as Pb(Mg1/3Nb2/3)O3-PbTiO3 (PMN-PT) or Pb(Zn1/3Nb2/3)O3-PbTiO3 (PZN-PT). For PMN-PT, compositions near the so-called morphotropic phase boundary, 011-cut and poled single crystals exhibit suitable characteristics (\( d_{31} \approx -1900 \times 10^{-12} \text{C/N} \) and \( d_{32} \approx +1000 \times 10^{-12} \text{C/N} \)). With such a substrate, the writing procedure is as follows: upon tensile/compressive stress (i.e., \( \sigma_{xx} - \sigma_{yy} > 0 \)), and assuming positive magnetostriction, the free energy exhibits a single minimum for \( \varphi = \pi \) (Fig. 2, left). Magnetization will then rotate toward the “1” state whatever its previous state was. Upon the removal of the stress, the state is preserved. Upon compressive/tensile stress (i.e., \( \sigma_{xx} - \sigma_{yy} < 0 \)), the minimum lies at \( \varphi = \pi/2 \) (Fig. 2, right), corresponding to the “0” state.

III. EXPERIMENTS

A schematic view of the device is shown at the top of Figure 3. As explained above, the stress is generated by a commercial PMN-PT substrate. Before further processing, one side of the substrate was mechanically polished to ensure a surface smooth enough for MOKE measurements. The magnetic element is a \( 10 \times (\text{TbCo}_{2.5(\text{nm})}/\text{FeCo}_{5(\text{nm})}) \) 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 substrate through a shadow mask by RF sputtering.
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 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 results are shown in Figure 3. It is characteristic of a uni-axial behavior with an anisotropy field of about 200 Oe. For this kind of layer, the magnetostriiction $\lambda_S$ is measured by laser deflectometry with the clamped beam technique and is about $10^{-4}$. The switching was evidenced using a MOKE setup to measure the projection of magnetization along the EA, while the polarizing field $H_S$ was applied on the HA, so as to define two stable positions. As shown in Figure 4, the system behaves as expected. When applying either positive or negative voltage pulses, tensile or compressive stress, respectively, is generated leading to a switch to “1” or “0.” One can also note that the state is kept upon removal of the voltage. Switching was obtained with 250 μs pulses, which is the shortest time allowed by the experimental setup.

IV. CONCLUSION

We have presented here the concept and experimental implementation of a device for a magnetoelectric memory cell using the effect of stress on anisotropy combined with the definition of 2 perpendicular stable positions in an anisotropic element. The writing of the information in the magnetic system is voltage controlled through the use of a 011-cut and poled PMN-PT relaxor substrate. 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. MOKE experiments evidenced the switching with sub-millisecond pulses. Since the information is stored magnetically, the readout can be made using GMR/spin valve techniques. Such an hysteretic giant magnetoresistance effect in a structure with two different values of anisotropy and submitted to mechanical stress was recently demonstrated. Biasing strategies for the magnetic polarization using FePt permanent magnet layers are also investigated.

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