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Nicolas Tiercelin, Yannick Dusch, V.L. Preobrazhensky, Philippe Pernod. Magnetoelectric memory using perpendicular magnetization states and magnetoelastic switching. *Journal of Applied Physics*, 2011, 109 (7), pp.07D7267. 10.1063/1.3559532 . hal-00591346

HAL Id: hal-00591346

<https://hal.science/hal-00591346>

Submitted on 25 May 2022

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Cite as: J. Appl. Phys. **109**, 07D726 (2011); <https://doi.org/10.1063/1.3559532>

Submitted: 24 September 2010 • Accepted: 30 November 2010 • Published Online: 01 April 2011

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Magnetolectric memory using orthogonal magnetization states and magnetoelastic switching

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(Presented 15 November 2010; received 24 September 2010; accepted 30 November 2010; published online 1 April 2011)

We present here a concept of a memory cell called MELRAM based on a magnetic element with giant magnetostriction, embedded in a piezoelectric matrix. Two equilibrium orientations of magnetization are defined by combining uniaxial anisotropy together with a magnetic polarization in the hard axis direction. Using the piezoelectric matrix, an anisotropic stress is created onto the magnetic element when applying a voltage across electrodes. 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. Micromagnetic simulations show the effect of applied stress on magnetization and theoretical feasibility of the device. Retrieval of information can be nondestructively made by giant magnetoresistance reading. Details of the principle, simulations, and performance perspectives are discussed. © 2011 American Institute of Physics. [doi:10.1063/1.3559532]

I. INTRODUCTION

Numerous efforts are made by research laboratories and industrials in order to develop the next generation of random access memories, possibly nonvolatile, low power consumption, high density, high speed, and robust, with a high retention time of the information. In a recent review paper, Kryder and Kim compare the different existing approaches and technologies for the next generation.¹ They describe the following solutions: ferroelectric RAM, magnetic RAM, spin torque transfer (STTRAM), phase change ram (PCRAM), carbon nanotube RAM, probe memories, holographic ram, copper bridge (CBRAM), resistive (RRAM), racetrack memory, one electron, molecular memory, and polymer memory. Among all these, the authors demonstrate that only RRAM, CBRAM STTRAM, and PCRAM seem to be viable in the long run. The list is omitting the use of multiferroic materials, possessing coupled ferroelectric and ferromagnetic phases.^{2,3} The interest of these materials is huge: one can write the information electrically using virtually “no energy,” and read the information via the magnetic system without destroying it. Up to date, very few materials with sufficient intrinsic multiferroic properties at room temperature were found suitable to be used in memory applications. The inclusion of multiferroic barriers into magnetic tunneling junctions shows interesting results, but still far below room temperature.⁴ Another way is to amplify the effect of a room temperature multiferroic such as Cr₂O₃ using interfacial properties in order to control the value of an exchange field. This led to a magnetolectric memory using electric field control and cooling through the Néel temperature.⁵ Additional studies led to an isothermal switching memory that is still required to be operated close to the Néel

temperature at 303 K.⁶ Another solution lies in the mechanical coupling of magnetic and ferroelectric materials known to operate properly in a wide range around room temperature. A few recent works^{7,8} related the effect of stress on the magnetic properties of some magnetostrictive materials, and tried to use it as a memory device, but could not achieve a simple switching procedure.

We introduce here a stress mediated magnetolectric memory cell: The information is written by the application of a voltage on the electrodes that leads to an electric field in the piezoelectric medium, which in turn generates stress on a monodomain magnetostrictive element. Depending on the sign of the voltage, the stress can change the anisotropy direction and thus cause the switching of magnetization between two equilibrium positions defined by a combination of anisotropy and polarizing magnetic field.^{9,10} The reading of the information can be done using well-known techniques, such as giant magnetoresistance (GMR), tunnel magnetoresistance, Hall effect, etc.

II. DETAILS OF THE MEMORY CELL PRINCIPLE

The geometry of a MELRAM cell is given in Fig. 1 and consists of a magnetic element with a defined easy axis (EA) direction, embedded in a piezoelectric matrix. The EA can be obtained by considering an ellipsoid-shaped element. The element has a high magnetostriction λ_S . Its size should not exceed about 100 nm to ensure a single domain behavior. The magnetic free energy of the system is described by the following equation:

$$F_{\text{mag}} = -MH_S \cos\left(\frac{3\pi}{4} - \varphi\right) - \frac{1}{2}MH_A \cos^2\left(\frac{\pi}{4} - \varphi\right) - \frac{3}{2}\lambda_S\sigma_{xx} \cos^2(\varphi), \quad (1)$$

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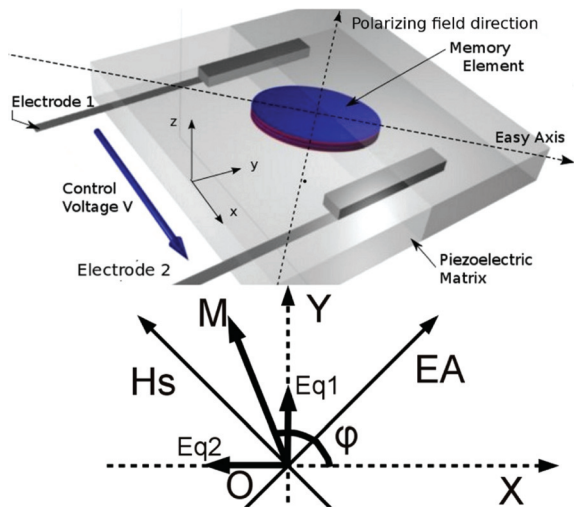


FIG. 1. (Color online) MELRAM cell configuration: The magnetic element and electrodes are embedded in a piezoelectric matrix.

where M is the magnetization of the element, making an angle ϕ with respect to OX , H_S is a polarizing field applied in the hard axis direction, H_A is the value of the effective anisotropy field, and σ_{xx} is the mechanical stresses applied to the element along the OX axis. The particular geometry and polarization of the piezoelectric material along the OX axis induces nonisotropic stresses on the magnetic element, e.g., tensile along the X axis and slightly compressive along the Y axis, or the opposite. For the sake of simplicity here, we consider $\sigma_{yy} = 0$ when writing Eq. (1). The external field H_S or equivalent 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. 2, 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 $OX-$ axes.

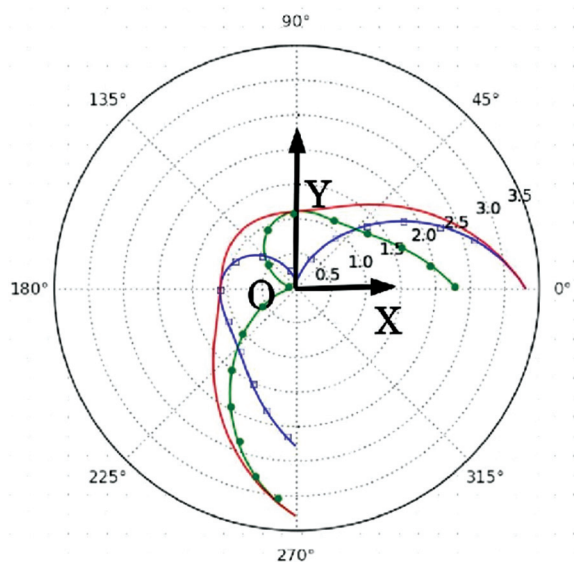


FIG. 2. (Color online) Magnetic free energy profiles (arbitrary units.) of the system as a function of the magnetization angle for three stress states. (—) No stress: two stable positions are defined for 90° and 180° . (Squares) Compressive stress along $OX \rightarrow$ anisotropy along OY , only the 90° position is stable. (Circles) Tensile stress along $OX \rightarrow$ anisotropy along OX , only the 180° position is stable.

applying a positive voltage, a positive stress is generated, thus removing the energy barrier between the two states and creating a unique energy minimum for $\phi = 90^\circ$. For a negative voltage, the stress is negative, and the minimum occurs for $\phi = 180^\circ$. When removing the voltage, the energy barrier is restored, ensuring the stability in the new state.

III. SIMULATIONS AND VIABILITY

In order to realize a first validation of the concept, both mechanical and magnetic simulations have been realized. First, electromechanical simulations with COMSOL MULTIPHYSICS 3.5 have been performed with the following parameters:

- magnetic element size: axis 45 and 25 nm, thickness: 20 nm, in-plane angle: 45° ;
- distance between electrodes: 130 nm;
- electrode length: 120 nm, height: 50 nm;
- material for electrodes and center element: copper. Young's modulus ≈ 110 GPa; and
- piezoelectric matrix thickness: 60 nm of Lead Zirconium Titanate (PZT).

Figure 3 shows the simulated generated stresses using the PZT matrix. When applying a 0.4 V voltage across the electrodes, a local strain reaching -1.2×10^{-3} can be generated corresponding to a compressive 100 MPa stress along OX . Conversely, when applying a -0.4 V voltage across the electrodes, a local strain reaching $+1.2 \times 10^{-3}$ can be generated corresponding to a tensile 100 MPa stress along OX . Moreover, it is important to note that the strain/stresses

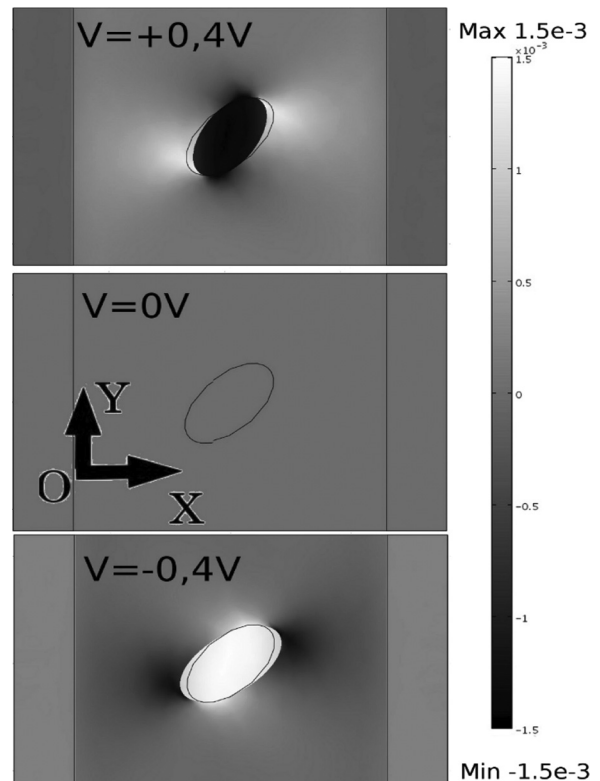


FIG. 3. Magnetic element strain in the piezoelectric matrix along the OX axis for three values of the driving voltage. Apparent deformation of the element is exaggerated. White: tensile strain, black: compressive strain.

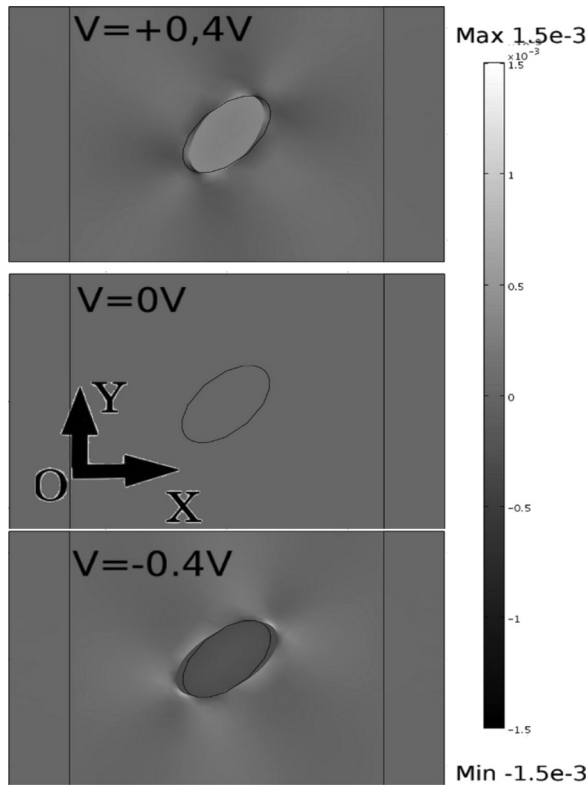


FIG. 4. Magnetic element strain in the piezoelectric matrix along the OY axis for three values of the driving voltage. Apparent deformation of the element is exaggerated.

applied on the magnetic element are anisotropic. Figure 4 shows the corresponding strains along OY for the same driving voltages. They are clearly negligible compared to the OX ones. Simulations also show that for this geometry, the maximum values of the electric field in the matrix never exceed the typical breakdown values for common PZT. This can allow further reduction of the memory cell.

These calculated values have been inserted along the magnetic properties into the MAGPAR¹¹ open source software, with the following parameters:

- magnetoelastic coefficients [typical for $TbFe_2$ (Ref. 12)]: $\lambda_{100} = 100 \times 10^{-6}$ and $\lambda_{111} = 1700 \times 10^{-6}$;
- saturation magnetization¹²: 1.2 T;
- exchange coupling (typical for rare-earth-transition metal alloys): 1.1×10^{-11} J/m; and
- bias magnetic field H_S : 150 kA/m = 1875 Oe.

The main results are given in Fig. 5. Application of the negative voltage inducing the tensile stress reinforces the anisotropy along the OX axis, as already predicted by Fig. 2. The micromagnetic simulation shows the switching along this direction. Application of the positive voltage provokes the switching along the OY direction. The switching occurs in whichever state the magnetization was in, and is stable in the new position when the driving voltage is removed.

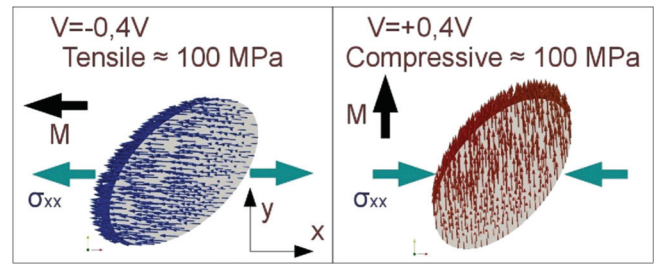


FIG. 5. (Color online) Effect of stress on magnetization. (Left) Tensile stress is generated, magnetization is switched and set in position 2. (Right) Compressive stress is generated, magnetization is set in position 1.

IV. CONCLUSION

We have presented here the concept of a device for a magnetoelectric memory cell using the effect of stress on anisotropy combined with the definition of two perpendicular stable positions in an anisotropic 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. As the information is stored magnetically, the readout can be made using GMR/spin valve techniques. Preliminary simulations 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/cm² per layer, low energy, nonvolatile 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. A patent is currently pending.¹³

ACKNOWLEDGMENTS

Y. Dusch's Ph.D. thesis is funded by the Direction Générale de l'Armement (DGA-France).

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