Гистерезисное магнетосопротивление в устройстве магнитной памяти, управляемой давлением

Ключевые слова: *магнетосопротивление, магнитная память, давление, мультиферроики*

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Представлена концепция записи данных в устройствах памяти, основанных на спин-реориентационных переходах в магнето¬резистивных пленках или мультиферроиках, управляемых давлением. Неразрушающее считывание информации осуществляется на основе эффекта шгантского магнетосопротивления. Принцип считывания продемонстрирован экспериментально на управляемой давлением слоистой наноструктуре.

Hysteretic magnetoresistance in stress controlled magnetic memory device

Keywords: *magnetoresistance, magnetic memory, pressure, multiferroics*

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We present here a concept of data recording in memory devices based on spin reorientation transition in magnetostrictive films or stress-mediated multiferroics. Retrieval of information can be non-destructively made by GMR reading. The principle of reading is demonstrated experimentally on a stress controlled $FeCo_{(2nm)}$ /$TbCo_{2(6nm)}$ /$FeCo_{(2nm)}$(2nm) /$Cu_{(3nm)}$ /$FeCo_{(2nm)}$ /$TbCo_{2(4nm)}$ /$FeCo_{(2nm)}$ nanostructured layer.

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Перейти к содержанию номера

Hysteretic magnetoresistance in stress controled magnetic memory device.

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We present here a concept of data recording in memory devices based on spin reorientation transition in magnetostrictive films or stress-mediated multiferroics. Two equilibrium orientations of magnetization are defined by the application of stress on a nanostructured film with uni-axial anisotropy and submitted to a magnetic polarization. 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. Retrieval of information can be non-destructively made by GMR reading. The principle of reading is demonstrated experimentally on a stress controlled $FeCo_{(2nm)}/TbCo_{2(6nm)}/FeCo_{(2nm)}/Cu_{(3nm)}/FeCo_{(2nm)}/TbCo_{2(4nm)}/FeCo_{(2nm)}$ nanostructured layer.

INTRODUCTION

As the need for energy efficient data processing and data storage booms, magneto-electric memories have raised tremendous interest among research teams. The latter could indeed combine the advantages of magnetic storage, such as non-volatility, speed and endurance, with energy efficient electric writing techniques. Intrinsic materials (with the notable examples of Cr_2O_3 and $BiFeO_3$) have been considered in several designs but offer only weak magnetoelectric response at room temperature and therefore require either cryogenic techniques[1] or precise control of the operating temperature[2]. On the other hand, composite materials, introduced by Boomgard et al. in 1976[3], use strain-coupled piezoelectric and magnetostrictive materials. They can operate at room temperature and offer several design possibilities. Most of the composite memory devices proposed either are toggle memories (i.e. whose initial state must be known prior to writing operation)[4] or use complex schemes using magnetocristalline anisotropy and epitaxial growth[5], or precisely synchronized driving signals[6].

In 2010, we proposed and patented an innovative memory device based on a composite structure comprising a nanometer sized magnetostrictive medium embedded in a piezoelectric matrix[7–10]. In particular, we showed that the competition between an external magnetic field and uni-axial magnetic anisotropy (obtained during sputtering under magnetic field) could be used to define two perpendicular equilibrium positions for magnetization and that stress could be used to switch between both positions in a deterministic fashion. The required magnetic configuration is shown in figure 1. The polarizing field H is applied perpendicularly to the easy axis of the layer. With a strength equal to $H = H_a/\sqrt{2}$ where H_a is the value of the anisotropy field, the competition between anisotropy and Zeeman energies gives rise to two equivalent stable positions $'1'$ and $'0'$ for magnetization M_{mem}. Magnetization can then be switched from one state to the other by the application of an anisotropic stress along the X axis. The stress threshold above which the switch can occur depends on the strength of the anisotropy, the magnetic field and the magnetostriction of the layer[11]. A tensile stress writes '1', whereas a compressive one writes '0'. The information is kept when the stress is realeased. The most efficient way is to use piezoelectric or electrostrictive stresses. A macroscopic device provided a proof of concept of this memory element[12] and demonstrated the writing principle using piezoelectric forces. The characterization of the magnetic state was performed using either a Vibrating Sample Magnetometer (VSM) or Magneto Optical Kerr Effect (MOKE). For practical memory applications, the magnetic polarization and the reading operation have to be closely integrated. Integration of magnetic biasing is under investigation[13,14]. This article addresses a reading strategy for such a device using a giant magnetoresistive (GMR) structure and demonstrates the possibility to read electrically the information stored in the memory element.

In the first section, we will present the details of the sample principle and preparation. The experimental setup will be described in the following section. In section III we will finally present and discuss the results of the experimental investigations showing that two magnetoresistance states can be obtained unequivocally through the application of compressive or tensile stress.

I. DEVICE PRINCIPLE

For a GMR-based reading strategy, the "memory" layer has to be associated to a "reference" layer with a pinned magnetization so that the switch from one state to the other induces a sufficient magnetoresistive contrast.

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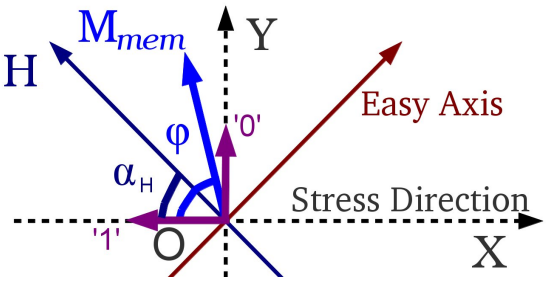

FIG. 1. Magnetic and Mechanical configuration of a memory cell. The polarizing field H is applied perpendicular to the magnetic easy axis and defines two stable positions. Tensile or compressive stress is applied to switch between states.

Such an approach and the influence of stress on spintronic structures have already been studied extensively to assess the influence of technological hazards or the potentialities for stress/strain sensors. In particular, Lohndorf et al. detailed the use of a magnetostrictive layer as part of GMR or Magnetic Tunnel Junctions (MTJ) spintronic structures for applications in sensor arrays[15,16]. However, in our case, the external magnetic field used to define the equilibrium positions of magnetization influences both the free layer and the fixed layer through the Zeeman interaction. Techniques must therefore be found to ensure the magnetoresistance contrast between the two stable positions. We consequently developed a technique based on two nanostructured magnetostrictive layers with exhibiting two different tailored anisotropies, for both the memory layer and the fixed layer of a current-in-plane GMR structure (CIP-GMR). It was shown in our previous work that given the strength of the anisotropy field H_a, the polarizing field H must have a minimum strength of $H = H_a/\sqrt{2}$ for the switch between stable positions to be possible. Thus the principle of the proposed device : a layer with a "low" anisotropy field H_{a1} will serve as the memory layer, whereas another with a "high" anisotropy H_{a2} will act as a reference. Setting the polarizing field H at $H_{a1}/\sqrt{2}$ and therefore much lower than H_{a2} will ensure that the reference layer will not switch during the writing operations in the memory layer.

II. DEVICE AND EXPERIMENTAL SETUP

In order to verify the feasibility of this concept, we fabricated a GMR structure consisting of two nanostructured layers with different engineered anisotropies separated by a copper spacer. This structure was deposited onto ($2mm \times 18mm \times 50\mu m$) thin silicon beams that were subsequently clamped at one end and pushed/pulled at the other end in order to induce tensile or compressive stresses. The setup schematic is given on figure 2.The nanostructured film was deposited onto the silicon by RF sputtering using a rotary turn table in a Leybold

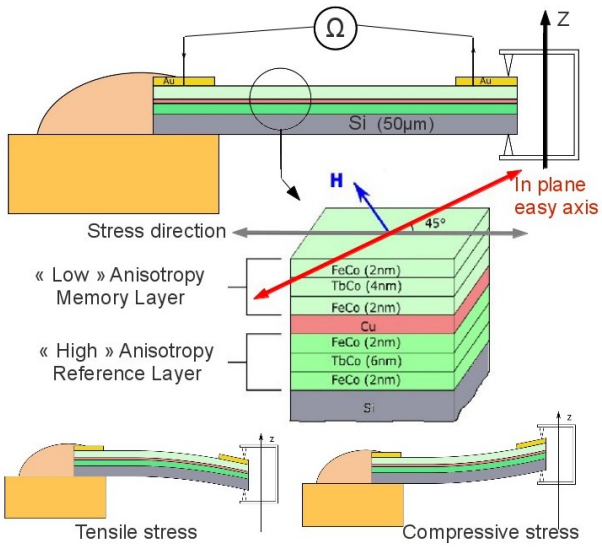

FIG. 2. Experimental device description

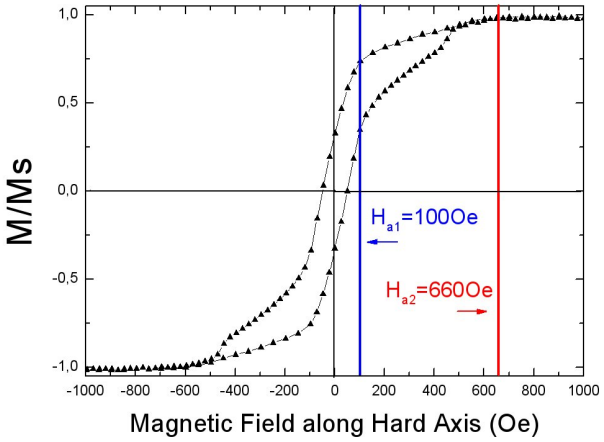

FIG. 3. Magnetization loop along the hard axis of the layer. Effective anisotropy field H_{a1} and H_{a2} of both trilayers can be determined by the slope variation.

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, along the length of the silicon beam. In order to tailor the magnetic properties[17–20], elementary layers of highly magnetostrictive $TbCo_2$ alloy are combined with layers of softer $FeCo$: changing the thickness ratio of these exchange coupled layers allows an adjustment of the resulting anisotropy field. The considered stack is thus $FeCo_{(2nm)}/TbCo_{2(6nm)}/FeCo_{(2nm)}/Cu_{(3nm)}/FeCo_{(2nm)}/TbCo_{2(4nm)}/FeCo_{(2nm)}$.

The films were characterized using the VSM and show a particular uni-axial behaviour. Figure 3 shows the magnetization loop along the hard axis (HA). Given the

structure of the film, and considering the copper spacer that breaks the exchange coupling at the interface, the HA characteristic with two slopes can be read as the superposition of two layers with different anisotropy fields. It can then be estimated that the bottom tri-layer has an anisotropy field of about $H_{a2} \approx 660Oe$, whereas the one exhibits $H_{a1} \approx 100Oe$. Thus in the device, the top trilayer will be the 'memory' layer, whereas the bottom will serve as a non switching reference layer.

To ensure a proper electrical contact, two gold pads were subsequently sputtered at the beam extremities through a shadow mask. One end of the cantilever is then glued on a non-magnetic brass mount to ensure a zero-displacement condition. The free tip is clamped by a brass pincer. The latter can be moved along the z vertical axis and can thus ensure a controllable displacement of the free tip. Measurements were typically done for displacements ranging from $-1.5mm$ to $+1.5mm$. As a result, compressive or tensile stresses can be applied on the magnetic layer. As detailed in the appendix, the strength of the created stress is not homogenous in the magnetic layer and decreases linearly along the length of the beam. Given the geometry and the material parameters, it is found that the deformation in the x direction is equal to $\epsilon_{xx}(x) \approx 3.5 \times 10^{-4}(1 - x/L)$ where L is the length of the beam. Considering a typical Young's modulus of $80GPa$ for this kind of layer, the generated stress can reach more than $25MPa$, which is sufficient to cause the switching of memory state[7].

The apparatus is then placed within the gap of an electromagnet producing a controllable homogeneous magnetic field. The direction of the field (i.e. angle with respect to the length of the beam) can also be adjusted manually. The gold electrodes were both connected to a Keithley 192 precision ohmmeter to continuously measure the magnetoresistance of the memory structure. The displacement of the free tip, as well as the applied magnetic field are both controlled through a Labview interface. With this setup, the magnetoresistance can be measured independently as a function of mechanical displacement or strength and direction of the external magnetic field.

III. MAGNETORESISTANCE MEASUREMENTS AND DISCUSSION

First, the magnetoresistive effect was estimated along the easy axis : figure 4 shows its variation as a function of the applied magnetic field. Given the structure of the magnetic film, decreasing the field from a saturated state first provokes the rotation of the magnetization in the top trilayer and an increase of the MR, for a lower negative field, the bottom trilayer magnetization also rotates thus restoring the lower value of MR. The maximum variation is about $(\Delta R/R)_{max} \approx 1\%$.

The following magnetoresistance measurements were done during stress cycles performed under several conditions. In figure 5, the magnetic polarizing field is applied along the hard axis with a strength ranging from 29 to 70 Oersteds. For lower field values ($29Oe$) no hysteresis behaviour is observed. It appears upon a slight increase of H ($33Oe$). Further increase first results in a better MR contrast along with a narrower curve. Over $70Oe$, the MR shows a high contrast but the hysteresis is too deprecated and the memory function is lost. Assuming the "reference" layer is not significantly affected by H, this is consistent with the predicted behaviour of the memory layer : As the anisotropy is constant, changing the polarizing field affects the angular positions of the two memory states '1' and '0'. For low values of H, the Zeeman interaction is too low, and the equilibrium positions are close to the easy axis. Even with a large applied stress, its required minimum value for the switching to occur is not met and no hysteresis is present. The shape of the measured resistance versus stress is consistent with a piezoresistive effect. When increasing H, the stable positions are farther from the EA, and the switching becomes possible with a sufficient stress. For higher values, the energy barrier between states is lower, and so is the required stress, hence the narrowing of the curve. Above $70Oe$, the "memory" layer is almost saturated because of its low anisotropy field, and the hysteretic behaviour disappears. For this configuration, $50Oe$ was found to be the optimum magnetic polarization.

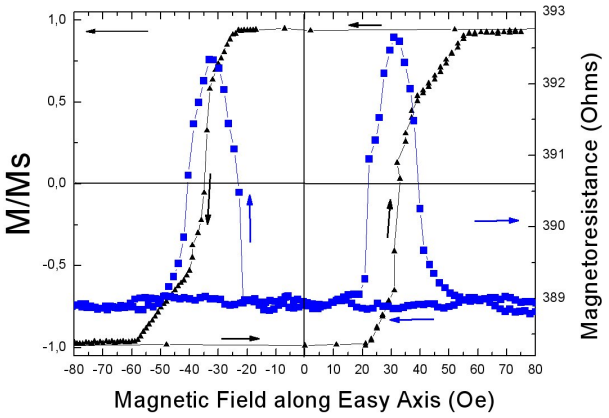

FIG. 4. Magnetization loop and Measured magnetoresistance along the easy axis of the layer. $(\Delta R/R)_{max} \approx 1\%$

In figure 6 the biasing field direction relative to the long side of the sample is changed from 45 to 60 degrees. Two phenomena are observed. First, the center of the hysteresis is shifted to the negative values of Z-displacement, which corresponds to tensile stress, and the magnetoresistance is globally shifted toward higher values. The fist effect can be understood by drawing the magnetic free energy of the "memory" layer, with the conventions of figure 1. Assuming that the stress in the OX direction, the volume energy can be written as the sum of Zeeman, anisotropy and magnetoelastic energy :

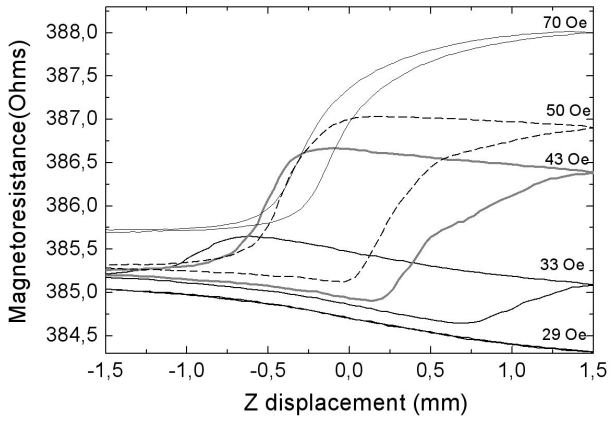

FIG. 5. Magnetoresistance loops as a function of magnetic bias.

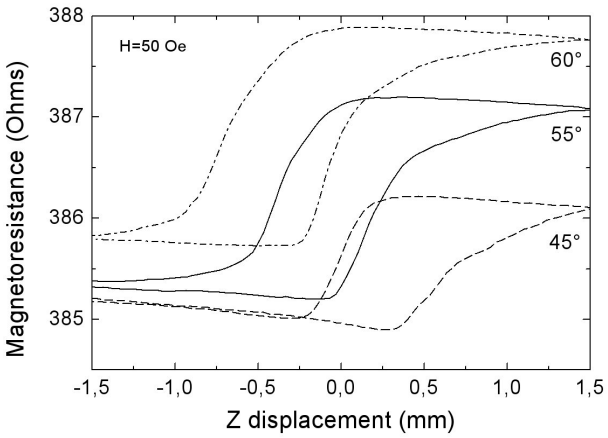

FIG. 6. Magnetoresistance loops as a function of magnetic bias angle.

$$F = -\mu_0 MH\cos(\varphi - \alpha_H) - \frac{1}{2}\mu_0 MH_{a1}\cos^2(\varphi + \pi/4) - \frac{3}{2}\lambda_S\sigma_{xx}\cos^2(\varphi) \quad (1)$$

where μ_0 is the vacuum magnetic permeability, M is the magnetization, making an angle φ with respect to the X axis, H is the polarizing field applied with an angle α_H with respect to the X axis, H_{a1} is the value of the effective anisotropy field, λ_S is the saturation magnetostriction of the layer and σ_{xx} is the mechanical stress applied along the X axis to the considered volume. In the ideal configuration, H is applied along the hard axis, *i.e.* $\alpha_H = 45°$. In that case, and for σ_{xx} equal to zero, the shape of the free energy presents two minima corresponding to the stable positions of magnetization (Figure 7, left). If H is mis-aligned, the energy profile becomes asymmetric, and there is one predominant energy minimum at zero stress. However, for an applied stress, the added magnetoelastic energy contribution is similar to an anisotropy contribution, and the system behaves as if the easy axis is rotated. In our case, the easy axis should rotate in the same direction as H was rotated, that is towards the X direction, which corresponds to a tensile stress. The hysteretic behaviour is thus restored with a shift toward the tensile stresses as it is measured. Moreover, given the used experimental setup, the stress distribution is not homogeneous in the layer (see earlier), and the phenomenon explained above does not occur in the whole layer. It means that the stress at the end of the cantilever is much lower than at the clamping point. Therefore, the effective rotation of the anisotropy axis mainly occurs in the latter zone, probably leading to the formation of magnetic domains, and to an area in the former zone where the magnetization is stuck in the $'0'$ position. As the $'0'$ corresponds to a higher resistance value (M_ref is pointing in the opposite direction), the total resistance of the device shifts toward higher values.

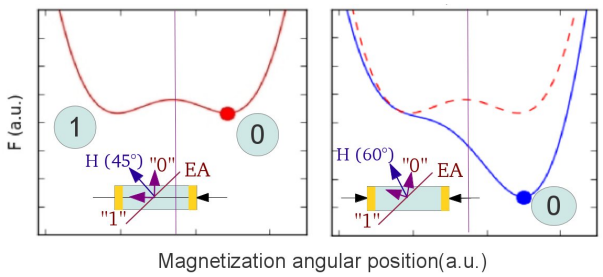

FIG. 7. Shape of the magnetic free energy of the system without applied stress as a function of the magnetization angle. Left : ideal configuration with H applied perpendicular to the Easy Axis, i.e. 45° with respect to X. Right : H is Misaligned by 15°, provoking a strong asymmetry in the energy profile.

Finally, we observed the influence of the magnetization orientation in the reference layer. As it presents a uni-axial behaviour, two possible directions are possible. Prior the stress cycle measurements, the sample was submitted to a magnetic field higher than H_{a2} in order to saturate M_{ref} in the desired direction. The results are presented on figure 8. The system behaves as expected. As a first approximation, the magnetoresistance can be expressed as $R = A - Bcos(\psi)$, where ψ is the angle between M_{mem} and M_{ref}. Thus, changing the sign of M_{ref} should invert the MR behaviour which is clearly observed on the measurements. It is to be noted that the piezoresistive contribution stays unchanged.

IV. CONCLUSION

Using a GMR effect, we have demonstrated here the possibility of reading electrically the information stored in a room temperature stress-operated magnetic memory device. In the proposed solution, a GMR sandwich was

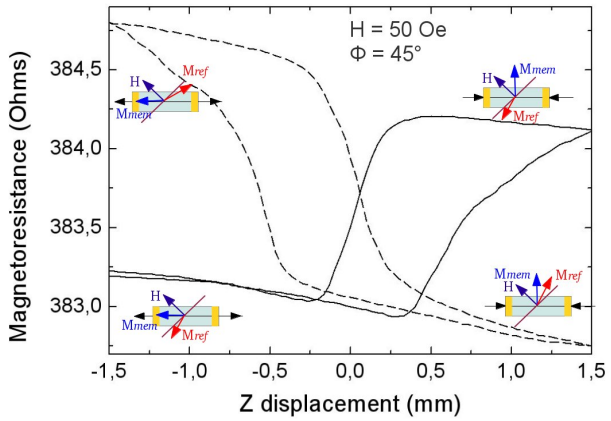

FIG. 8. Magnetoresistance loops depending on the original orientation of the reference layer.

realized using 2 nanostructured tri-layers with tailored uni-axial anisotropies. A "low" anisotropy layer was used as a memory layer, whereas a "high" anisotropy was induced for the reference layer. Measurements of the magnetoresistance versus stress clearly showed an hysteretic behaviour demonstrating the memory effect. Influence of the polarizing field alignment and reference layer orientation was observed and explained. Further investigations of this principle will be led in stress mediated magnetoelectric memory devices.

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APPENDIX: CALCULUS OF STRAIN IN THE MAGNETOSTRICTIVE LAYER

Let us consider a cantilever with a length L and a thickness d clamped at the $x = 0$ position and driven by an external force applied along the z axis at the $x = L$ position. The calculation aims at finding the stress distribution at the surface of the beam, *i.e.* $z = d/2$. The vertical displacement of the cantilver along **z** is given by $U(x)$. The displacement satisfies the equilibrium equation :

$$\frac{\partial^4 U}{\partial x^4} = 0$$

The boundary condition at $x = 0$ gives

$$U|_{x=0} = 0 \quad \text{and} \quad \left.\frac{\partial U}{\partial x}\right|_{x=0} = 0.$$

Therefore, the displacement profile $U(x)$ can be written: $U(x) = Ax^2 + Bx^3$. The null momentum boundary con-

dition at $x = L$ gives:

$$\left.\frac{\partial^2 U}{\partial x^2}\right|_{x=L} = 0 \text{ and consequently } B = -\frac{A}{3L}$$

$$\text{thus } U = Ax^2 - \frac{A}{3L}x^3.$$

The displacement of the beam end at $x = L$ is equal to $U_L = \frac{2}{3}AL^2$ and thus $A = \frac{3}{2}\frac{U_L}{L^2}$ which leads to the expression of the displacement profile :

$$U(x) = \frac{3U_L}{2L^2}(x^2 - \frac{1}{3L}x^3).$$

The longitudinal deformation at the vertical position z can then be obtained :

$$\varepsilon_{xx} = -z\frac{\partial^2 U}{\partial x^2} = -3z\frac{U_L}{L^2}(1 - \frac{x}{L}).$$

As a result, the deformation in the magnetic film situated at $z = d/2$ is expressed as

$$\varepsilon_{xx}|_{d/2} = -\frac{3}{2}\frac{dU_L}{L^2}(1 - \frac{x}{L}).$$

For the conditions of our experiment $d = 50\mu m$, $L = 1.8cm$, $U_L = 1.5mm$, the deformation is equal to

$$\varepsilon_{xx}|_{d/2} \approx 3.5.10^{-4}(1 - \frac{x}{L}).$$

This value is comparable with the saturation magnetostriction of our giant magnetostrictive nanostructured layer.