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IMPROVING THE DATA STORAGE PERFORMANCES WITH LAYERED NANOWIRES FOR SYNTHETIC ANTIFERROMAGNETIC RACETRACK MEMORIES

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Abstract. Racetrack memories based on synthetic antiferromagnets have been studied, representing structures with high storage performances due to the increased velocity of the domain wall (DW) in the nanowires. The active stack of layers in the nanowire was: magnetic layer (CoFeB, CoFe, Co/Ni/Co, Co/Ni) / heavy metal layer (Ru, Pt, Pd) / magnetic layer. The strong spin–orbit coupling, the interface phenomena and the spin Hall effect are interdependent and generate together a spin current and a torque which move the DW with speed controlled by the thickness of the heavy metal layer and the composition of the ferromagnetic layer. The applied field was of (–2…+2) kOe and the propagation current density of ($-0.8\cdot10^{12}$ A/m^2… $+0.8\cdot10^{12}$) A/m^2. DW velocity obtained by simulation methods was represented *versus* the domain width δ and the Walker breakdown field H_W. Maxima of about 1000–1200 m/s were reached under a specific configuration for different composition of the magnetic layer. Modifications caused by the control parameters were registered and discussed. High values of velocity maxima can be obtained by correlation between the parameters characterizing the phenomena implied in the DW motion process in the nanowire. Values of $(0.6–2)\cdot10^3$ A/m for H_W, respectively of 3–8 nm for δ it appear to be favorable in order to obtain velocity maxima for the considered materials.

Key words: racetrack memory, synthetic antiferromagnets, spin Hall effect, simulation model, domain wall velocity, ferromagnetic layer, configuration.

1. INTRODUCTION

Since 2010, notions like perpendicular magnetic anisotropy (PMA) in magnetic thin films and magnetic tunnel junction are linked on the superior speed racetrack memories, for which different magnetic materials are used. These are materials with the magnetic easy axis perpendicular to the plane of the nanowire: materials with bulk magnetocrystalline anisotropy; magnetic glasses with atomic pair ordering; magnetoelastic materials; and thin layers or atomically engineered multilayers with interface anisotropies [1]. The latter category of manufactured structures demonstrated superior performances and facilities [1, 3, 4].

Method for increasing the DW velocity can be considered:

– having more narrow DW – in materials with high magnetic anisotropy, such as Co/Ni superlattices;

– using of stacks of magnetic layers (*e.g.* Co or CoFeB) or Co/Ni/Co sandwiches on underlying heavy metal layers (Pt, Pd, Ir, W, Ta, etc.) where the DW velocity can be controlled by varying the thickness of the heavy metal layers and the composition of the magnetic layer [3].

– reducing the net moment of the synthetic antiferromagnets (SAFs) to zero or closed, formed from two PMA sub-racetracks which are antiferromagnetically coupled *via* an ultrathin heavy metal layer (*e.g.* Ru). The magnetic moments are mirror-image in the two sub-racetracks and are carefully tuned to vanish the net magnetization.

Following the idea, the racetrack memories based on SAFs are structures with high storage performances due to the increased velocity of the DWs in the nanowires. The null net magnetic moment of the stack of alternate layers allows developing of huge DW velocities inside. In plus, velocity can be controlled by geometry and constituents nature, as we have illustrated in the followings, constructing a nanostructural model of the racetrack nanowires and using simulation methods.

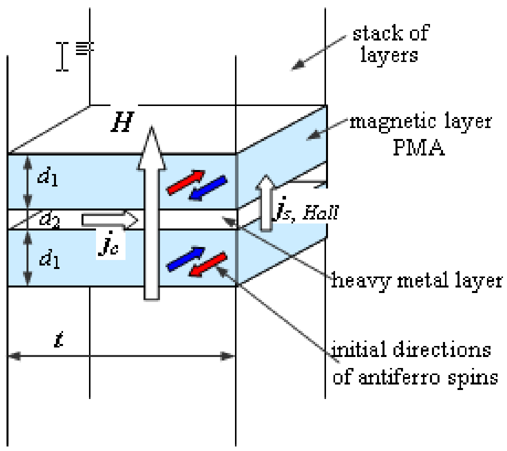
2. SIMULATIONAL MODEL

In our case, the simulation model reconstructs structure (the nanowire) at lattice level, describes interactions and forces between constituents (inter- and intra- stack of layers) and sets the excitation (the applied field and the propagation current) for properties determinations (DW velocity). In the second step, the control parameters (constituents geometry and nature) are varied in order to obtain the variation of the measured quantities (material response at excitation) in the domain of interest and help us to decide on the optimal internal and external parameters values for which the response is the desired one for a specific application.

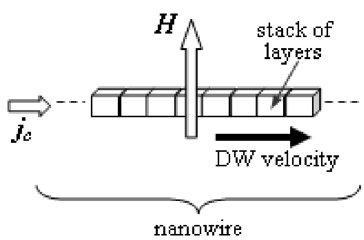
We have studied the following active stacks in the SAF structures for racetrack memories: magnetic layer (CoFeB, CoFe, Co/Ni/Co, Co/Ni) / heavy metal layer (Ru, Pt, Pd) / magnetic layer (DW are mirrored).

The model has to consider two effects. The first is represented by the interaction: antiferromagnet–electric current. Exchange interaction occurs between conduction electrons (in the electric current) and DW magnetizations which determine torques moving the spins and consequently a magnetization dynamics [11]. The second effect considers the DW moving in antiferromagnet under the influence of the electric current, when we have dissipative or non-adiabatic coupling between magnetization and current. The DWs velocity is proportional to the current and no pinned [11].

The simulational scenery at microscopic level includes the parameters values characterizing four phenomena derived from spin–orbit coupling, which determine the DWs displacement by a chiral spin torque [1, 2, 7]: the strong spin-orbit coupling at interfaces magnetic layer–heavy metal layer generates PMA; the Dzyaloshinsky-Moriya interaction (DMI) between these layers determines perpendicular orientation of neighboring moments across the DW (chiral Néel-type structure); the interdependence of the DMI strength and the proximity-induced magnetic moment within the heavy metal layer; generation of a spin current $j_{s,\ Hall}$ within the heavy metal layer by a spin Hall effect (spin–orbit scattering of the conduction electrons occurs, spin currents being transverse to both the conduction current j_c and spin) – Fig. 1a). The spin current diffuses into the magnetic layers determining the rotation of the moments within DW towards the spin direction (transverse on the stack of layers), then the DMI exchange field generates a torque and all the DWs move in the same direction along the wire [1, 7]. Consequently, the DW motion (direction and velocity) can be controlled by: the magnitude and sign of the chiral effects, the spin Hall effect and the DMI. These effects and interactions depend on two parameters which were the control parameters in our study: the nanometric thickness of the heavy metal layer and the constituents of the ferromagnetic layers. The DW speed is limited only by demagnetizing fields at DWs level and this effect were considered here only as a decay factor, taken from literature [8, 9, 11, 20].



a)



b)

Fig. 1 – a) The active stack of layers: two PMA antiferro layers are joined by a ultrathin heavy metal layer. The directions of the applied field H and propagation current j_c are indicated and also the generated spin Hall current; b) nanowire in the racetrack memory.

The stack of PMA layers are placed one near to another along the racetrack memory, along the propagation current path. The DW speed is parallel with this current and transverse on the stacks (Fig. 1b). The current is supposed to be uniform through the structure.

Simulations were based on the finite element method, implemented with help of the HFSS 3D simulator (Ansoft Technologies). The characteristic dimensions for the nanowire compounds were considered of: thickness of magnetic layers d_1 = 2.8 nm, thickness of heavy metal layer d_2 = 0.8 nm, nanowire width t = 350 nm. The mesh was set at 16.6 × 16.6 × 22.4 nm^3 per cell (chosen to overall the exchange interaction length for the magnetic layers in the stack). The excitations levels were: the applied magnetic field H = (–2…+2) kOe (over the Walker breakdown field limit for the considered materials) and the propagation current $j_c = (-0.8\cdot 10^{12} \ldots +0.8\cdot 10^{12})$ A/m^2.

The DW speed can be estimated with the formula [11]:

$$\langle v \rangle \cong \frac{\beta}{\alpha} v_J - \frac{\sqrt{\left(1-\beta/\alpha\right)^2 v_J{}^2 - \left(\gamma\delta/2\right)^2 H_k^2}}{1+\alpha^2}, \qquad \beta > \alpha, \tag{1}$$

$$v_J = \frac{\mu_B \cdot P \cdot j_c}{e \cdot M_S}, \tag{2}$$

where v_J is the spin current velocity, P = spin polarization percentage of the tunnel current, and M_S is the saturation magnetization, j_c = propagation (shifting) current density, H_k = anisotropy field, μ_B = Bohr magneton, e = elementary charge, α is the Gilbert damping constant, β = nonadiabatic coefficient, γ is the gyromagnetic ratio $[\mathrm{m/C}]_{\mathrm{SI}}$, δ is the width of DW, H_k = anisotropy field.

We can estimate the dynamic domain with width formula:

$$\delta = \sqrt{A / K_{eff}}, \tag{3}$$

where $K_{eff} = K_u - \mu_0 M_S^2/2$, with K_u = uniaxial anisotropy constant, μ_0 = = permeability of the free space and A = exchange interaction constant (exchange stiffness).

The exchange interaction length, $l_{ex} = \sqrt{\dfrac{2A}{\mu_0 \cdot M_s^2}}$ (around 10–15 nm) was verified to overall the thickness of the multilayers in the stack, in order to allow ferromagnetical coupling of the magnetic layers.

The maximum velocity given by theory is [8, 11]:

$$v_{\max} = v_{H\max} + v_J = \frac{\gamma\delta}{\alpha} H_W + v_J, \tag{4}$$

where H_W is the Walker breakdown field, $H_W = \alpha \cdot H_k / 2$. These values, obtained for different racetrack constituents, were compared with the results obtained by simulation for the proposed model.

3. RESULTS FOR THE DW MAXIMAL VELOCITY

Structures of synthetic antiferromagnets racetrack memories were studied by micromagnetic simulation on the basis of the model constructed by us using HFSS 13.0 [1, 14]. The simulational data were compared with results obtained by theoretic calculus and the data given by literature [8, 10, 11]. The parameter of interest was the velocity of the domain wall motion which is increased in SAF racetracks at high values due to the giant exchange coupling torque driving the DWs.

The results obtained for the DW velocity v *versus* the DW width δ and *versus* the Walker breakdown field H_W are given in Figs. 2, respectively 3. The domain for δ was considered of (2 …12) nm, respectively the domain for H_W was of (700 … 3800) A/m (equivalent with $\mu_0 \cdot H_W$ = (0.879 … 4.775) mT). Graphs were represented only in the positive domain of the excitation (for positive values of H and j_c) because by inverting the field / current sense phenomena and numerical values are similar (only some senses of the forces, currents and torques are inverting, too, while the absolute values remain the same). Values of the parameters of interest for velocity calculus, estimated in similar conditions [8, 12, 13, 21], etc., were given in Table 1.

Table 1

Parameters for the considered material combinations in the SAF racetrack memories, for thicknesses of the magnetic layers d_1 = 2.8 nm, respectively of heavy metal layer d_2 = 0.8 nm (data from literature)

magnetic layer/heavy metal layer \ **parameter →**	α	β	P	M_s [A/m]	H_k [Oe]	γ [$\mu_0 \cdot 2\pi \cdot$ Hz/T]	A [J/m]	K_u [J/m^3]
$Co_{40}Fe_{40}B_{20}$ / Ru [II]	0.012	0.40	0.52	$1.50 \cdot 10^6$	$1.200 \cdot 10^3$	$1.875 \cdot 10^{11}$	$1.8 \cdot 10^{-11}$	$8.41 \cdot 10^5$
Co/Ni / Ru	0.014	0.36	0.47	$0.86 \cdot 10^6$	$1.116 \cdot 10^3$	$1.798 \cdot 10^{11}$	$1.7 \cdot 10^{-11}$	$8.00 \cdot 10^5$
$Co_{70}Fe_{30}$ / Pd [I]	0.012	0.40	0.53	$1.70 \cdot 10^6$	$1.750 \cdot 10^3$	$2.102 \cdot 10^{11}$	$1.0 \cdot 10^{-11}$	$2.00 \cdot 10^5$
Co/Ni/Co / Pd	0.022	0.38	0.50	$1.06 \cdot 10^6$	$1.987 \cdot 10^3$	$1.671 \cdot 10^{11}$	$1.9 \cdot 10^{-11}$	$8.27 \cdot 10^5$
$Co_{70}Fe_{30}$ / Pt [III]	0.012	0.40	0.53	$1.72 \cdot 10^6$	$1.720 \cdot 10^3$	$1.835 \cdot 10^{11}$	$1.5 \cdot 10^{-11}$	$1.70 \cdot 10^5$
Co/Ni/Co / Pt	0.045	0.38	0.49	$0.66 \cdot 10^6$	$1.956 \cdot 10^3$	$1.760 \cdot 10^{11}$	$2.0 \cdot 10^{-11}$	$4.10 \cdot 10^5$

[I, II, III] – first, second and third optimal solutions for the velocity maximum, found by simulations when the DW width is varied.

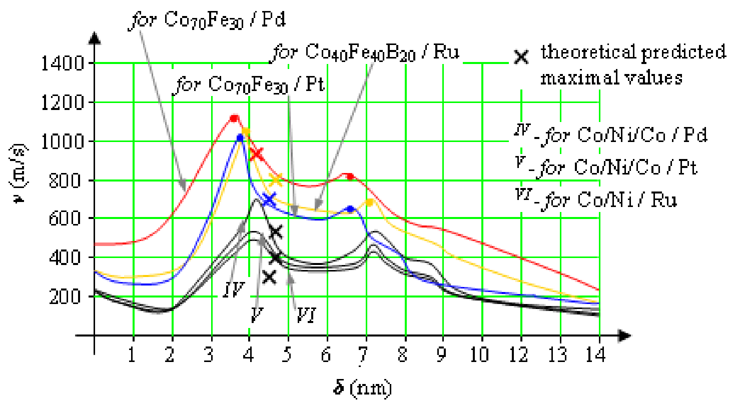


Fig. 2 – Evolution of the DW velocity in function of the dynamic domain with δ for the considered materials, for a level of excitation of: H =1.2 kOe and $j_c = 0.5 \cdot 10^{12}$ A/m^2.
The velocity peaks (maxima) can be observed (colored circles).
The maxima theoretically predicted are also indicated on graph.

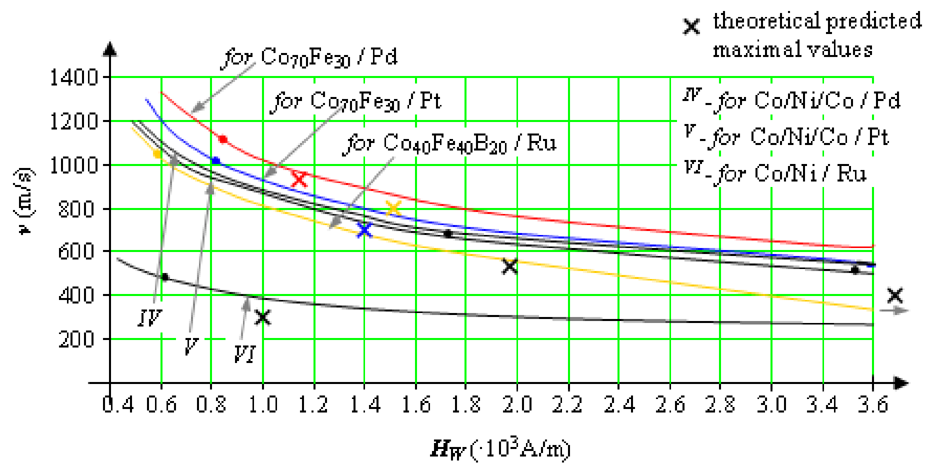


Fig. 3 – Evolution of the DW velocity in function of the Walker breakdown field H_W for the considered materials, for a level of excitation of: H =1.2 kOe and $j_c = 0.5 \cdot 10^{12}$ A/m^2 .
The DW width corresponds to the maximum indicated in Fig. 2 for each material sample.

More than one maximum was obtained on the graphs in Fig. 2 due to the fact that the DW motion is a resonant phenomenon. The motion occurs with maximum speed around the resonances, which depend on magnetic layer nature and the exchange interactions. Our simulations have illustrated that resonance positions, imposed by the crystalline structure of the ferromagnet, are correlated with electromagnetic properties of the underlying heavy metal layer due to the strong layers coupling that generates PMA. We have to point out that DW velocity maxima occur at lower values for the DW width, the dynamic of the DW being increased by the intensified interaction forces which are inverse proportional with δ.

Evolution of the DW velocity in function of the Walker breakdown field illustrates significant velocity increasing at lower Walker breakdown fields, which are difficult to be obtained in practice and involves correlation of a lot of parameters and excitation level [7, 10]. These correlations will be discussed in the next section. When these condition are satisfied, the velocity increasing at structure level is a very good one and represents a step to more qualitative devices.

By analyzing the graphs, one observes that, due to the correlation of the electromagnetic parameters, the order of the materials (stack of layers) for which the maximum velocity occurs by adjusting one parameter do not necessary correspond to the material order for which velocity values are in the same relation when we adjust another parameter. The conclusion is also valuable considering the whole domain of variation for the other parameters (*e.g.* when H_W field decreases, v is not increasing for different materials at the same rate like in the case of the δ decreasing).

At macroscopic level, of great interest are the graphs of the DW velocity in function of the control parameters of the structure: the nanometric thickness of the heavy metal layer d_2 = 0.6 … 2 nm, respectively the constituents of the ferromagnetic layers (CoFeB and Co/Ni with Ru; CoFe and Co/Ni/Co with Pd or Pt) – influence described by velocity dependence on the grain size g in the polycrystalline magnetic thin films. Results obtained by simulation and verified by calculus and data from literature [3, 4, 5] are given in Figs. 4 and 5.

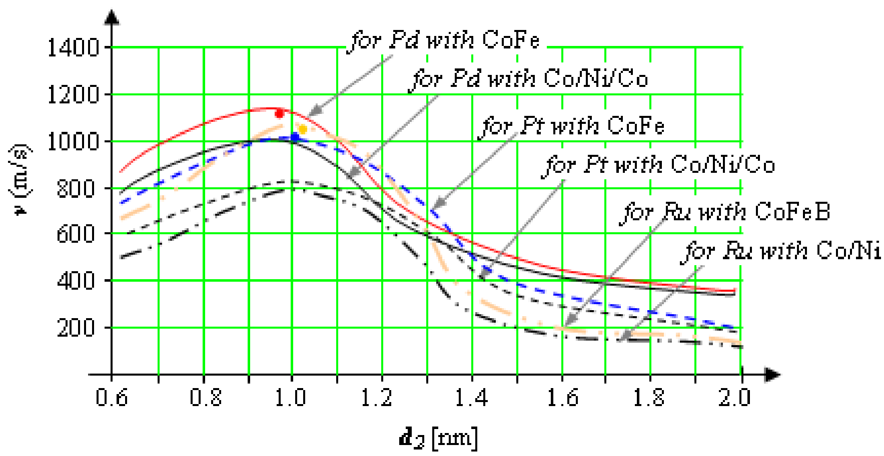


Fig. 4 – Dependence of the DW velocity on the nanometric thickness of the heavy metal layer d_2, which represent a control parameter of the structure. Velocity maxima obtained in graphs in Fig. 2 (colored circles) can be observed in the peak zone of the curves represented here.

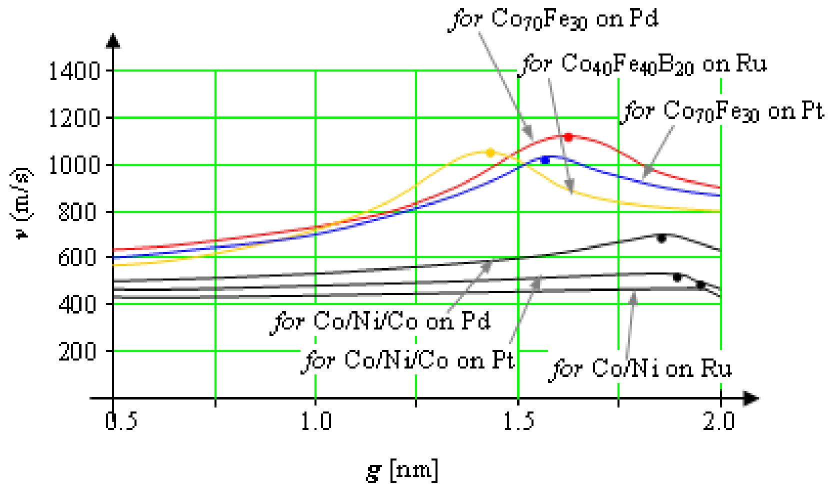


Fig. 5 – Dependence of the DW velocity on the nanometric thickness of the grain size *g* in the polycrystalline magnetic thin film. Velocity maxima obtained in graphs in Fig. 2 (colored circles) can be observed in the peak zone of the curves represented here.

The graphs in Fig. 4 illustrates the fact that ultrathin heavy metal layers are recommended for obtaining the PMA effect in the stack, an increased spin current within the heavy metal layer and consequently high DW velocities in the racetrack memory. The maximum velocity peak is wide and is shifting in function of the nature of the heavy metal layer, the effect of the coupled magnetic layers on the peak position being minimal. The nature of the heavy metal layer influences the maximal and minimal velocity levels on the curves, which are also dependent on the coupling.

Materials can be considered correlated to create the maximum effect of velocity increasing when at least a maximum (a colored circle) obtained in evolution curves from Fig. 2 is present on the corresponding curve in Fig. 4 in the peak zone. In our simulation method, the material parameters for the considered pair of ferromagnetic / heavy metal layers were correlated in order to obtain this effect.

For obtaining the dependence of the DW velocity on the grain size *g* in the polycrystalline magnetic thin film (Fig. 5), the crystalline structure of the ferromagnets has to be considered. A nano-crystallization of body-centered cubic (BCC) (110) was simulated in our model in the case of CoFeB, the CoFe was represented fcc phase (111), while the Co/Ni(/Co) succession of layers was represented hcp (hexagonal close-packed) / ccp (cubic close-packed) [5, 22]. An average grain size in the range of 0.5…2 nm was considered for the thin polycrystalline magnetic layers and also the report between the average grain sizes of this different materials but obtained in the same conditions of crystallization [10, 19, 21]. (The lattice constants are around 2–4 Å for all analyzed magnetic layers, values which are at least ten time smaller than the magnetic layer thickness, d_1. Polycrystalline layers in the racetrack memory stacks have to be fine manufactured with grain sizes at most of a few nanometers, smaller than the layer thickness.)

Curves in Fig. 5 are optimal, in the sense described above (the velocity maxima obtained in graphs in Fig. 2 can be identified in the peak zone of the curves represented in Fig. 5), due to the correlation of parameters.

In fine manufactured ferroelectric materials, DW velocity has a tendency of increasing with the grain size g, at low values of g, due to the fact that in bigger grains the walls are moving faster, favoured also by the presence of not so many boundaries. If the grain dimensions are growing forwards, DW motion is slow down due to the interactions between neighbor domains and magnetocrystalline anisotropy. Velocity maxima for different materials evolve in an order which can be described as follows: materials with lower velocity maxima can be manufactured with a little greater grain sizes (the compromise: manufacturing price against performances).

A set of punctual values, theoretical predicted, are present on each graph. One observes that the existing theory gives us much inferior values for DW velocity due to the lack of material parameters correlation and not including the description of al the physical phenomena implied in the DW motion. Simulation offers us the advantage of obtaining results after parameter correlation within the simulation modeling and the optimization of the results in function of these parameters.

As a conclusion of different material couple comparison, the solution with $Co_{70}Fe_{30}$ on Pd it appears to be the best from the point of view of performances concerning the DW velocity in a device for data storage.

4. DISCUSSION

The obtained results are indicating us a series of methods for increasing the DW velocity in the racetrack memory devices based on SAFs, methods which will be commented in the followings:

– decreasing of the Walker breakdown field H_w; both simulation and theory illustrate consistent improving of the DW motion in samples with low Walker field limit. It is important how far of the Walker breakdown limit is the applied field in order to obtain superior values of the field induced velocity component. A solution for extending the Walker breakdown limit is the use of antiferromagnetic materials with strong coupling in the racetrack nanowires (SAFs in our case);

– decreasing of the DW width δ; but v variation with δ is strongly nonlinear. If we are far from resonances, only a low reduction of δ is a solution. The presence of resonances on the $v(\delta)$ curves is important, ensuring high increasing of the DW velocity if resonant values for δ are reached. Here a careful tuning of the parameters is necessary in order to complete this task;

– the Gilbert damping decay (decreasing of α) and increasing of β; here materials with low α, respectively high β has to be chosen;

– increasing of excitation (j_c, respectively H), but only in the domain inside which their efficiency is maximum. This domain can be determined by simulation.

Also, the DW velocity v increases when H_W and δ are decreasing. These parameters depend on magnetocrystalline anisotropy originating in the spin-orbit interactions. This dependence implies that the values for the anisotropy field H_k has to be low, but uniaxial anisotropy constant K_u has to be high (it means high energy per unit volume for magnetization after one axis), while the exchange interaction constant A has to be low and M_s also low. But we have also to consider that the spin-orbit coupling effect is weak in comparison with exchange interaction, the influence of the A parameter on the DW width being stronger.

These criteria have been demonstrated in practice [4, 6, 10], etc. and have been found by us by simulation methods. The theoretical formula it appears to be incomplete, not describing the interdependence of the material parameters (given in Table 1) in the final formula for DW velocity. Theory can only indicate how have to be other parameters, like α and β, in order to obtain high values of DW velocity.

The H_W and δ parameters can also be reduced by increasing the excitation (H and j_c) due to the thin film effect [16].

In the same time, H_W depends on the demagnetizing field strength in the nanowire, which depends on the nanowire thickness and the tunneling effect. The linked depinning field depends on the potential gradient along the stack of layer [17].

The H_W is linked on Gilbert damping, the α coefficient also decreasing when H_W decreases. Following the idea, one remarks that α, the Gilbert damping constant, is independent of the exchange bias field. The DW velocity is dependent on Gilbert damping but the dependence can be described only is we know the dependence on the excitation (applied field and current) and H_W – the strong interdependence of parameters.

The width of the domain walls, δ, is finite and is determined principally by exchange and magnetocrystalline energy. It is also dependent on the grain size in the polycrystalline magnetic thin film and indirectly on the saturation magnetization and demagnetizing field (which depend on film thickness) [18]. The grain size refinement reduces effective anisotropy (linked on K_u), increasing the ferromagnetic exchange coupling [16, 18, 23], and due to this fact the necessity of compromise solutions appears. The δ value can be changed by modifying the applied field H.

We have to consider that, as a consequence, δ increases with the exchange interaction length l_{ex}, which has to be correlated with the grain size.

In its turn, the grain size g in the polycrystalline magnetic thin film is linked on anisotropy and saturation magnetization (increases with K_u and is inverse proportional with M_s).

Another parameter, P can be considerably increased by tunneling effects between the thin layers. The tunneling causes also the anisotropy increasing. The spin polarization percentage of the tunnel current, P, is also dependent on the j_c and has to be high for obtaining high values for the v_J component.

The α and K_u parameters depend strongly on the heavy metal layer thickness, d_2, (K_u increases when d_2 decreases, but α decreases when d_2 decreases) [15].

We have also a dependence of the maximum speed, v_{max} on the gyromagnetic ratio γ. The γ parameter depends on magnetic material nature (through the magnetic dipole moment of the material), and in our case on the spin – torque coupling (which influences the effective angular momentum).

In conclusion, the most important thing is the parameter correlation in order to obtain superior values for the DW velocity. This task can be optimally accomplished by simulation methods, based on a proper conceived simulation model. All the enumerated dependences represent the criteria of material choosing, based on simulation results.

5. CONCLUSIONS

Synthetic antiferromagnets presenting perpendicular magnetic anisotropy in their magnetic thin films are good candidates for racetrack memory devices with high storage capabilities, due to an increased DW velocity in the active layers. The active stacks of layers in the nanowire were considered as: magnetic layer (CoFeB, CoFe, Co/Ni/Co, Co/Ni) / heavy metal layer (Ru, Pt, Pd) / magnetic layer and a good correlation between the structural and functional parameters is necessary in order to obtain the effect of velocity increasing, under an external excitation (field and current).

A consistently increasing of the DW velocity by parameters tuning at structure level was demonstrated by simulation methods, considering like control parameters the thickness of the heavy metal layer and the composition of the ferromagnetic layer.

The necessary correlation between the parameters characterizing the phenomena implied in the DW motion process in the nanowire imposes the following levels of these parameters:

- decreased Walker breakdown field H_W (ensured by adopting SAFs);
- DW width δ rather low, or better close to a resonance (achieved by tuning carefully the electromagnetic parameters of layers and by modifying the applied field H);

- low the Gilbert damping (decreased α) and increased nonadiabatic coefficient β (is a matter of material choosing);
- increased excitation (high applied field H, respectively propagation current j_c), in the domain of their maximum efficiency;
- low anisotropy field H_k, but high uniaxial anisotropy constant K_u;
- low exchange interaction constant A and saturation magnetization M_s and demagnetizing field also low;
- low nanowire thickness;
- rather low grain size in the polycrystalline magnetic thin film (by grain size refinement, reducing of the effective anisotropy and increasing the ferromagnetic exchange coupling are to be avoid);
- low exchange interaction length l_{ex};
- increased spin polarization percentage of the tunnel current;
- low heavy metal layer thickness, d_2 (ensures high K_u and low α);
- high gyromagnetic ratio γ (ensures high maximum of the DW velocity).

As a final conclusion, one remarks that simulation methods, based on the model conceived by us, impose themselves like a nondestructive instrument of analysis for parameters choosing, correlation and structure optimization (from the point of view of geometry and constituents).

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REFERENCES

1. S. Parkin, S.-H. Yang, *Memory on the racetrack*, Nature Nanotechnology **10**, 195–198 (2015).
2. X. Zhang, G. P. Zhao, H. Fangohr, J. Ping Liu, W. X. Xia, J. Xia, F. J. Morvan, *Skyrmion-skyrmion and skyrmion-edge repulsions in skyrmion-based racetrack memory*, Scientific Reports **5**, 7643 (2015).
3. Z. Sun, *High-Performance and Low-Power Magnetic Material Memory Based Cache Design*, Dissertation, University of Pittsburgh Swanson School of Engineering, 2013.
4. N. Ben-Romdhane, W.S. Zhao, Y. Zhang, J-O. Klein, Z.H. Wang, D. Ravelosona, *Design and Analysis of Racetrack Memory Based on Magnetic Domain Wall Motion in Nanowires*, IEEE/ACM Int. Symp. on Nanoscale Architectures (NANOARCH'14), 71–76, 2014.
5. Evgeny Y. Tsymbal, Igor Zutic (Eds.), *Handbook of Spin Transport and Magnetism*, CRC Press, 2011.
6. S.K. Kurinec, K. Iniewski (Eds.), *Nanoscale Semiconductor Memories: Technology and Applications*, CRC Press, 2013.
7. Y. Zhang, W. S. Zhao, J.-O. Klein, C. Chappert, D. Ravelosona, *Current induced perpendicular-magnetic-anisotropy racetrack memory with magnetic field assistance*, Applied Physics Letters **104**, 032409 (2014).
8. Z. Meng, M. Kumar,J. Qiu, G. Han, K. L. Teo, D.-T. Ngo, *Domain wall motions in perpendicularly magnetized CoFe/Pd multilayer nanowire*, J. Phys. D: Appl. Phys. **47**, 345001 (2014).

9. S. Parkin, *Highly Efficient Current Induced Domain Wall Motion in Synthetic Antiferromagnetic Racetracks*, Conference Materials Science & Technology 2014, October 12–16, Pittsburgh, PA.
10. A. Swaving, *Spin Transport and Dynamics in Antiferromagnetic Metals and Magnetic Insulators*, PhD Thesis, Institute for Theoretical Physics, Utrecht University, 2012.
11. W. Zhao, G. Prenat (Eds.), *Spintronics-based Computing*, *Technology & Engineering* (Ch: "Current induced Magnetic Switching for High-Performance Computing", pp. 1–52), Springer, 2015.
12. T. Devolder, P.-H. Ducrot, J.-P. Adam, I. Barisic, N. Vernier, Joo-Von Kim, B. Ockert, D. Ravelosona, *Damping of $Co_xFe_{80-x}B_{20}$ ultrathin films with perpendicular magnetic anisotropy*, Applied Physics Letters **102**, 022407 (2013).
13. E. Barati, M. Cinal, D. M. Edwards, A. Umerski, Calculation of Gilbert damping in ferromagnetic films, EPJ Web of Conferences **40**, 18003 (2013).
14. D. Ionescu, G. Apreotesei, *A Novel Simulational Approach: Electromagnetic Parameters Determinations for Some Ferrite-Ferroelectric Nanocomposites*, Rom. Rep. Phys. **65**, *4*, 1328–1347 (2013).
15. S. Mizukami, X. Zhang, T. Kubota, H. Naganuma, M. Oogane, Y. Ando, T. Miyazaki, Gilbert *Damping in Ni/Co Multilayer Films Exhibiting Large Perpendicular Anisotropy*, Appl. Phys. Express **4**, 013005 (2011).
16. A. Mougin, M. Cormier, J. P. Adam, P. J. Metaxas, J. Ferré, *Domain wall mobility, stability and Walker breakdown in magnetic nanowires*, EPL, Europhysics Letters **78**, *5*, 57007 (2007).
17. X.-P. Ma, H.-G. Piao, J.-H. Shim, D.-H. Kim, S. K. Oh, S.-C. Yu, *An Effect of Demagnetizing field on the Dynamic Bahavior of Domain Walls in Ferromagnetic Nanowires*, Proc of the Int. Conf. Nanomeeting, Physics, Chemistry and Application of Nanostructures: 2011, Minsk, Belarus, 26–29 May, p. 62.
18. D. Navas, C. Redondo, G. A. Badini Confalonieri, F. Batallan, A. Devishvili, Ó. Iglesias-Freire, A. Asenjo, C. A. Ross, B. P. Toperverg, *Domain-wall structure in thin films with perpendicular anisotropy: Magnetic force microscopy and polarized neutron reflectometry study*, Phys. Rev. B **90**, 054425 (2014).
19. S. Cojocaru, *Effect of Boundary Conditions on Magnetization of a Nano-Size Ferromagnet*, Rom. Rep. Phys. **64** (Supplement), 1207–1211 (2012).
20. W. Kappel, M. M. Codescu, D. Popa, *Losses in Sintered NdFeB Magnets*, Rom. Rep. Phys. **56**, *3*, 391–398 (2004).
21. Yuan-Tsung Chen, C. C. Chang, *Effect of grain size on magnetic and nanomechanical properties of $Co_{60}Fe_{20}B_{20}$ thin films*, Journal of Alloys and Compounds **498**, *2*, 113 (2010).
22. B.Y.C. Wu, P.J. Ferreira, C.A. Schuh, *Nanostructured Ni-Co Alloys with Tailorable Grain Size and Twin Density*, Metallurgical and Materials Transactions A **36A**, 1927 (2005).
23. D.-T. Ngo, Z. L. Meng, T. Tahmasebi, X. Yu, E. Thoeng, L. H. Yeo, A. Rusydi, G. C. Han, K.-L. Teo, *Interfacial tuning of perpendicular magnetic anisotropy and spin magnetic moment in CoFe/Pd multilayers*, Materials Science (2013); arXiv:1304.6156 [cond-mat.mes-hall].