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Invited Lecture

New solutions for perpendicular magnetic recording media

H. GAVRILĂ[*]
University "Politehnica" of Bucharest, Splaiul Independenței 313, RO-060042, Romania

While the most promising longitudinal recording systems cannot surpass the theoretical limit of about 200 Gb/in^2 for areal recording density and the demand for higher densities is permanently increasing, it is evident that the perpendicular magnetic recording constitutes the realistic issue to the longitudinal one. The perpendicular magnetic recording offers significant advantages relative to the previous conception, among them the most important being stronger write and read fields, and therefore the use of media of higher anisotropy, smaller grain size, higher signal-to-noise ratio, and a better thermal stability. Unfortunately, the perpendicular recording has to cope some important physical and technological difficulties. To overcome them, many ingenious solutions were recently proposed. Two of these proposals, regarding the perpendicular media, are analysed in the paper: the composite media and the coupled granular/continuous media.

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1. Introduction

Recently, Samofalov et al. [1] proposed systems of permanent magnets generating strong magnetic fields to create the heads for recording on high coercive media. In the basis of calculations made for different magnetic systems, the possibility of dense longitudinal and perpendicular recording was grounded.

While the most promising longitudinal recording systems, which use the antiferromagnetically coupled (AFC) thin film media [2], cannot surpass the theoretical limit of about 200 Gb/in^2 for areal recording density, it becomes more and more obvious that perpendicular magnetic recording represents the immediate alternative to longitudinal recording. Perpendicular magnetic recording offers many meaningful advantages for high-density recording relative to the longitudinal one [3,4]. Among the most significant advantages, one can mention the fact that it uses single pole heads that are able to generate stronger fields, which, in turn, allows for (and even imposes) the use of media of higher anisotropy. Together with the advantage of smaller grains, which means a much higher areal grain density at a given energy barrier, this also leads to a higher signal-to-noise ratio (SNR) at an imposed thermal stability.

Nevertheless, to become really commercial, perpendicular recording also encounters some important physical and technological difficulties. For example, it is difficult to ensure the (necessary) close alignment of the uniaxial anisotropy axis with the recording field. In the ideal case of the perfect alignment, the ratio between the stabilizing energy barrier ΔW and the write field energy is

$$\xi = 2\frac{\Delta W}{\mu_0 H_s M_s V}, \qquad (1)$$

where H_s is the write field, M_s is the saturation magnetization and V is the volume of the grain.

Tilted media can be a way to solve this problem. Indeed, considering only a single grain, a tilting of the easy axis can increase the value of this ratio; at an inclination of 45°, which represents the optimal configuration, ξ draws near to 2 [5,6]. In other words, this kind of media can increase nearly two times the energy barrier to the superparamagnetic effect as compared to conventional perpendicular media. Unfortunately, due to some great technological difficulties, these media have a limited horizon of application. However, there are other media configurations, which have the same good potential for perpendicular recording as tilted media. It is the case of *perpendicular composite media*, which will be analysed in Section II.

Another reason that impedes the complete valorisation of the superior potential of perpendicular recording is the noise due to the irregularities of bit transitions. In the case of longitudinal recording, the media with positive exchange coupling have "noisy" transitions, whose configuration is imposed by the requirement of minimization of magnetostatic energy. On the contrary, in perpendicular recording, transitions have a reduced magnetostatic energy and, therefore, the noise can be reduced with the help of dense networks of uniformly distributed pinning sites, even if the control of such pinning configurations is practically very difficult to achieve. With longitudinal media, the alloying and a very careful processing can ensure the weakening of the exchange coupling, the reduction of the grain size, the avoidance of the clustering of grains, and the reduction of noise. With granular perpendicular media, whose grain size was lowered even below 10 nm, the irregularity of the transitions is more marked due to intergranular exchange coupling (which leads to large magnetic clusters), to the distribution of the anisotropy field, as well as to the write field gradient. Then, one may try to reduce the transition noise by reducing the cluster size, that is by reducing more and more the grain size and by improving the magnetic segregation of grains (but to the prejudice of thermal stability), or by increasing the head field gradient.

For perpendicular media without intergranular exchange, the fundamental physical limit is imposed by thermal instability (superparamagnetic limit). An evaluation based on the current values of the anisotropy able for writability [7] assigns for the areal recording density the same limit as above-mentioned of about 200 Gb/in^2. It results that, even if the grains are completely decoupled, perpendicular media have a quite short lifetime, which would drastically limit their viability.

Nevertheless, exchange interactions can be used to extend this limit [8] since they improve the thermal stability. Numerical simulations suggest that the exchange interactions, if uniform, can also improve the SNR. If the intergranular exchange coupling is directly controlled, only by grain segregation, the increased thermal stability is accompanied by the reduction of SNR. An alternative to this situation is offered by the *continuous/granular coupled* (CGC) *media*, where using a continuous thin film indirectly controls the intergranular exchange. It has been experimentally proved that CGC media, initially proposed as a solution for controlling the stability of continuous thin film media [9,10], have a better thermal stability without damaging their SNR [10]. The two approaches are different, but the explanation is still missing. The analysis of the behaviour of the CGC media is done in Section III.

2. Perpendicular composite media

The *composite perpendicular medium*, proposed by Victora and Shen [11], is a granular medium, in which each grain is made up of a magnetically soft lower region (1) and of a magnetically hard upper region (2).

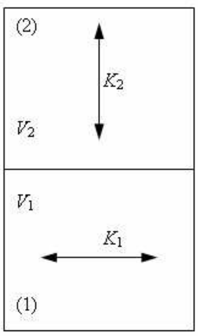


Fig. 1. The sketch of the magnetization of the grain of a composite medium.

Let us first consider the magnetization configuration of the grain represented in Fig. 1, assuming that both regions are magnetically hard. Within an exterior field with the intensity H, the total energy of the composite grain is:

$$W = -J_{exc}\cos(\theta_2 - \theta_1) + K_2 V_2 \sin^2\theta_2 + K_1 V_1 \sin^2\theta_1 + \\ + \mu_0 H M_2 V_2 \cos\theta_2 + \mu_0 H M_1 V_1 \cos\theta_1 \; ; \quad (2)$$

K_2 and K_1 represent the uniaxial anisotropy constants of the two regions, while M_1 and M_2 represent their saturation magnetizations; θ_1 and θ_2 are the angles formed between the two magnetizations and the applied field, and J_{exc} represents the exchange constant between the two regions. The switching field is obtained by annulling the derivatives $\mathrm{d}W/\mathrm{d}\theta_2$, $\mathrm{d}W/\mathrm{d}\theta_1$, $\mathrm{d}^2W/\mathrm{d}\theta_2^2$ and $\mathrm{d}^2W/\mathrm{d}\theta_1^2$, an operation that is quite difficult to perform analytically.

At $H = 0$, the energy minimum corresponds to the solutions (0,0) and (π,π), which represent two stable states of the grain magnetization configuration: $\mathbf{M}_1$ and $\mathbf{M}_2$ both oriented $\uparrow$ (state **1**), respectively $\downarrow$ (state **2**). When applying a field H $\downarrow$, the energetic minimum (0,0) changes, pointing out the tendency of the $\mathbf{M}_1$ and $\mathbf{M}_2$ magnetizations to be oriented according to the direction of the field. The switching field H_s represents the value of the applied field for which this energetic minimum disappears, the only energetic minimum corresponding to state **2**.

The increase of the ratio between the anisotropy constants K_2/K_1 also leads to an increase of the ξ ratio. If $K_2/K_1 = 1$, the maximum value of ξ is about 1.2, but if $K_2/K_1 \to \infty$ it results that $\xi \to 2$, which justifies why the lower region 1 should be made of a magnetically soft material ($K_1 \to 0$).

If we take: $V_2 = V_1 = V/2$, $M_1 = M_2 = M$ și $K_1 = 0$, equation (2) becomes:

$$W = -J_{exc}\cos(\theta_1 - \theta_2) + \frac{1}{2}K_2 V \sin^2\theta_2 + \frac{1}{2}\mu_0 M H V(\cos\theta_1 + \cos\theta_2) \; . \quad (3)$$

Using the notations: $j = J_{exc}/(K_2 V)$ and $h = \mu_0 M H/(2K_2)$, this equation can be also written as follows:

$$\frac{W}{K_2 V} = -j\cos(\theta_1 - \theta_2) + \frac{1}{2}\sin^2\theta_2 + h(\cos\theta_1 + \cos\theta_2), \quad (4)$$

the energy barrier being

$$\Delta W = \frac{1}{2}K_2 V \; . \quad (5)$$

The smallest normalized switching field, whose value is $h_s = 0.3$, corresponds to $j = 0.38$. It is obvious that one should prefer a weak exchange interaction J_{exc}, which suggests the introduction between the two regions of a thin film made of a material that can be polarized, the same as with AFC media [12]. Corresponding to the condition of annulling the derivatives $\mathrm{d}W/\mathrm{d}\theta_2, \mathrm{d}W/\mathrm{d}\theta_1$, $\mathrm{d}^2W/\mathrm{d}\theta_2^2$ and $\mathrm{d}^2W/\mathrm{d}\theta_1^2$, it results:

$$h_\mathrm{s} = \frac{\sin^2\theta_2\cos^2\theta_2 + \cos^2 2\theta_2}{2\cos^3\theta_2}. \tag{6}$$

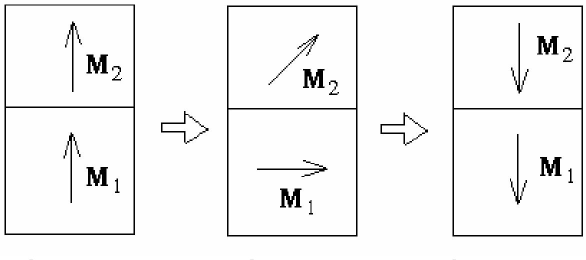
If $\theta_2 = \arccos\sqrt{\left(\sqrt{5}-1\right)/2}$, we obtain $h_{\mathrm{s,minim}} = 0.3003$, and the corresponding value of the ξ ratio is 1.67.

Fig. 2 shows the switching process in the ideal case. When applying the field, the magnetization $\mathbf{M}_1$ begins to rotate, thus changing the angle of the exchange field applied to region 2. In turn, this field also determines the rotation of the magnetization $\mathbf{M}_2$. In order to increase further the value of the ξ ratio, one should search for the optimal values of the V_2/V_1 and M_2/M_1 ratios.

The effect of volume ratio V_2/V_1. Composite media have a much smaller switching field as compared to conventional perpendicular media because the magnetization of the magnetically soft region 1 can be more easily switched, thus producing an exchange field that accelerates the rotation of the magnetization of the magnetically hard region 2. This exchange field contains a term inversely proportional to the V_2/V_1 ratio, so that a decrease in this ratio leads to an increase in the exchange field, and therefore to a decrease in the switching field. But the decrease in the V_2/V_1 ratio also reduces the energy barrier ΔW, and that is why one should look for a compromise value.

The highest value of the ξ ratio is obtained at $V_2/V_1 \cong 0.1$, with $j \cong 0.12$; the ξ ratio does not depend very much on the values given to j, therefore one can expect that small deviations of the thickness of the intermediary exchange layer, or of the compositions of the material, etc. may not seriously harm the performances of the medium. Although in this case the ξ ratio is very much close to 2, a very small value of the volume V_2 would require an excessively high anisotropy constant K_2 in order to achieve good thermal stability.

Taking this into account, we have further agreed on $V_2/V_1 = 0.5$.



$h = 0.03$, $\theta_2 = \theta_1 = 0$ | $h = 0.3$, $\theta_2 = 38°$, $\theta_1 = 90°$ | $h = 0.5$, $\theta_2 = \theta_1 = 90°$

Fig. 2. The switching process in the optimal case (j = 0.38) with $V_1 = V_2$ and $M_1 = M_2$ (according to [10]).

The effect of magnetization ratio M_2/M_1. The exchange field produced by the magnetization $\mathbf{M}_1$ is increased as the value of this magnetization increases, and it is decreased when the value of the magnetization $\mathbf{M}_2$ increases, so that one may expect better results at small values of the M_2/M_1 ratio. Indeed, we obtain high values of the ξ ratio if M_2/M_1 = 0.1…0.3. Thus, for example, for $M_2/M_1 = 0.2$ and $j = 0.45$ it results that $\xi = 1.95$. Again, the value of the ξ ratio does not depend greatly on the variation of j: for j = 0.3…0.7, it results that ξ = 1.7…2.

When the two magnetizations are different, $M_1 \neq M_2$, the normalized field h can be defined by the following relation

$$h = \mu_0 \frac{H\langle M\rangle}{2K_2}, \text{ with}$$

$$\langle M\rangle = \frac{M_1V_1 + M_2V_2}{V_1 + V_2}. \tag{7}$$

The effect of anisotropy ratio K_2/K_1. For the materials that can be physically made, the anisotropy constant K_1 is never null. Simulations (with $V_2/V_1 = 0.5$, M_2 = 200 kA/m, M_1 = 1 MA/m, K_2 = 2 MJ/m^3, J_{exc}/V = 0.9 MJ/m^3) have shown that the ξ ratio increases greatly at the beginning when the ratio between the K_2/K_1 anisotropies increases from 1 to 10, and then it shows a tendency for saturation [10]. With ultrahigh density recording systems, where the use of composite media is proposed, one expects that the anisotropy of the magnetically soft material is a perpendicular shape anisotropy, which appears to be exactly the direction along which the highest value of K_1 is tolerated. When the easy axis is longitudinally oriented, the thermal energy barrier is much smaller than that corresponding to the perpendicular orientation.

Thus, it is necessary to check that $K_1 < 0.1\ K_2$ is achieved in practical applications.

The effect of the distribution of the easy axes orientation. With perpendicular media, a special issue is raised by their extreme sensitivity to the orientation of the easy axes: a slight deviation of this orientation leads to a large change in switching field. Thus, an increase from 0 to 1° of the β angle formed by the easy axis and the applied write field produces a decrease in the switching field from H_K to 0.92 H_K. This marked sensitivity also leads to a decrease in SNR. On the contrary, media tilted at 45° show great tolerance at the deviation of the easy axis, the same as with the suggested composite media.

When the β deviation is 0…10°, the switching field remains practically unchanged. When $\beta = 0$, the switching field is 548 kA/m (using the same values for the other parameters as above). With a perpendicular medium having the same values of the magnetization and of the uniaxial anisotropy as the average values of the magnetization $\langle M\rangle$ = 733 kA/m and of the anisotropy constant $\langle K_\mathrm{u}\rangle$= 0.67 MJ/m^3 belonging to the composite medium considered above, it results that the switching field is $2K_u/(\mu_0\langle M\rangle)$ = 1.46 MA/m, that is about 2 times higher than with the composite medium. This means that we may use a material of extremely high anisotropy in order to produce a composite medium capable of very high recording densities. Moreover, the fact that extremely tilted fields find it difficult to switch these media will greatly reduce the effect of erasing adjacent tracks, which is probably the most important problem encountered in high density recording so far [8,13].

The magnetization cycles of the two regions, which are both markedly rectangular, prove the existence of a large nucleation field that inhibits the appearance of reversed magnetization fields even at the centre of the large bits. This also ensures a low d.c. noise. The corresponding curves also prove that the magnetically soft region begins to switch before the magnetically hard region.

Besides, simulations have proved that the magnetization $\mathbf{M}_1$ begins to rotate sooner than $\mathbf{M}_2$. At a certain value of the θ_1 angle, the exchange field is strong enough, so that when it is added to the applied field, it surpasses the switching field of the magnetically hard region; subsequently, the magnetizations $\mathbf{M}_2$ and $\mathbf{M}_1$ switch simultaneously and abruptly. Using the same switching field and the same applied field, and if the applied field just slightly surpasses the switching field, the composite medium switches about 4 times faster than the conventional perpendicular medium. However, if the write field is much larger than the switching field, this difference is greatly reduced.

Finally, this analysis has also proved that when using a single pole head to write in the composite medium (which happens currently in perpendicular recording), the switching is much easily produced at the centre of the head than around its edges.

3. Continuous/granular coupled media

Perpendicular continuous/granular coupled (CGC) media are made of a continuous layer C, of thickness *c*, without pinning centres, exchange coupled with a perpendicular granular layer G, whose thickness is *g* (Fig. 3), both films being placed onto a soft magnetic underlayer (SUL). This structure combines the useful properties of perpendicular continuous and granular media: the small grains of the G layer, which are stable as a result of their coupling with the C layer, provide dense pinning centres for the walls in the C layer. Since the grains cannot reverse their magnetization at the centre of the bit without nucleating a domain in the C layer, the thermal stability of the CGC medium is better than that of a decoupled granular medium [14].

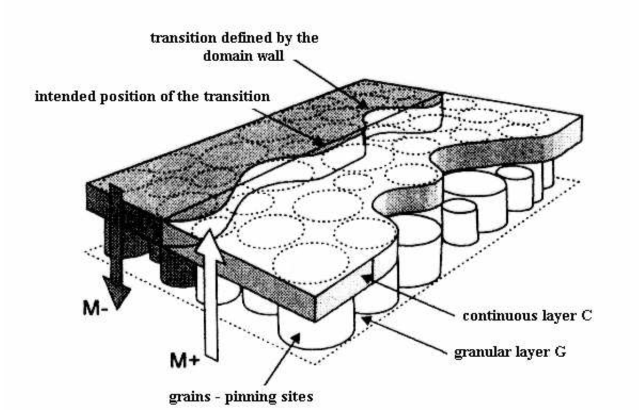


Fig. 3. The principle representation of a CGC medium. The location of the domain wall (of the transition) in the C layer is imposed by the orientation of the grains magnetization in the G layer (according to [16]).

The recorded magnetic transition has a dual structure, which consists of a usual structure in the G layer and of a domain wall in the C layer. The two transitions overlap so that the transition in the continuous C layer is pinned by means of the one in the granular G layer: the domain wall in the C layer can be moved only if reversing the magnetization of the grains in the G layer. Thus, the size of the unity switching at the transition is given by the size of the grains in the G layer, and the shape of the transitions at the surface of the CGC medium is given by the limits of the same grains (Fig. 3). However, recent simulations [14] have shown that, under certain circumstances, the tendency to minimize the energy of the walls leads to a reduction of the irregularities of bit transitions in the case of CGC media. The wall in the C layer moves away from the limits of the grains, so that the transition noise is reduced too [15]. This proves that the direct relationship between thermal stability and noise can be broken in a controlled way, thus evading the conventional limits of the recording density.

Since the two films are exchange coupled, the domain wall in the C layer moves away from the grains limits only if the magnetization of the grains moves away from the direction of their easy axes. It has been assumed that there is a Bloch wall, and that the remagnetization of the grains takes place by coherent rotation [16]. The last hypothesis is extremely simplistic, since remagnetization is a much more complex phenomenon, but it represents a satisfactory first approximation for the length scale of the process.

The energy of the wall in the C layer, whose areal density is

$$\sigma_p = \sqrt{A_C K_{u,C}}\ , \tag{8}$$

where A_C and $K_{u,C}$ represent the exchange and the uniaxial anisotropy constants of the material in the C layer, is directly related to its area. At a given thickness *c*, it is proportional to the length of the wall, so that a plane wall is energetically preferable. The energy of the transition is minimum when the reduction of the wall energy is compensated by an increase in the anisotropy energy, which is for every grain

$$W_{\mathrm{g}} = K_{\mathrm{u,G}} V \cos^2 \theta , \qquad (9)$$

where $K_{\mathrm{u,G}}$ represents the anisotropy constant of the G layer, V is the grain volume, and θ represents the angle between the grain magnetization and its easy axis. The reduction of the bit transition irregularities is done by means of a mechanism controlled by the process of minimizing the energy of the domain walls. The degree to which the irregularities are reduced depends on the ratio between the wall energy and the energy barriers existing in the G layer, so that at a given total thickness of the medium, the effect can be controlled by simply varying the ratio $\rho = c / g$ between the thicknesses of the two composing layers. At a given wall energy, the transition irregularities can also be reduced by reducing the exchange energy between the two layers, but the effect is quite weak, and it can be left aside [17].

Three mechanisms of smoothing the wall shape in the C layer have been identified [15,18]. They differ according to the way of altering the magnetic state of magnetization in the G layer. Considering the same total thickness of the CGC medium, but a different ratio $\rho = c / g$ between the thicknesses of the two composing layers, these mechanisms are:

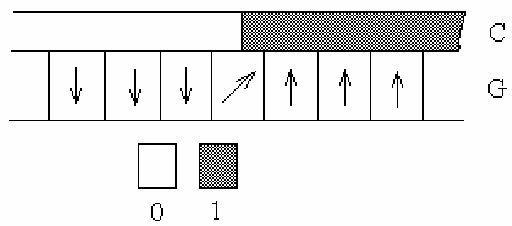


Fig. 4. The schematic representation of the mechanism of reversible smoothing.

(i) *Stable reversible smoothing*, corresponding to a low value of the ρ ratio: the force acting on the domain wall causes the inclination of magnetization relative to the normal on the medium plane, inclination that is also transmitted to the grains of the G layer (Fig. 4). However, the wall energy is low, so that the corresponding force is sufficient only for producing a reversible change of magnetization. This smoothing reduces the irregularities that can be observed at the surface of the C layer more than in the G layer, where the transition closely follows the irregularities of the well-segregated grains.

(ii) *Stable irreversible smoothing*, which corresponds to the optimal value of the ρ ratio: The stronger force acting on the domain walls lets the head field surpass the energy barriers associated to the grains that would otherwise contribute to increasing the irregularities or the apparent size of the cluster. This is similar to an increase in the head field gradient, allowing for the conversion of big clusters into smaller unities. When the head field is removed, the walls no longer move because the force acting on them is not enough in order to reverse the magnetization of the grains in the G layer.

(iii) *Unstable irreversible smoothing*, high values of the ρ ratio: The force onto the wall is further increased, supporting the action of the head field, as in the previous case. But now, when canceling the head field, this force is strong enough in order to reverse the magnetization of the grains in the G layer. Subsequently, the walls are mobile enough so that they can find positions of a relative energetic minimum, at a certain distance from the desired location of the transition, especially at the corners of the transition zone. This leads to curving the transition, and produces an additional noise.

Measurements based on the Kerr effect have proven that when the ρ ratio increases, one obtains a higher inclination of the hysteresis cycle at the coercivity point and a better rectangularity $S^* = M_{\mathrm{r}} / M_{\mathrm{s}}$, which leads to improved thermal stability and writing sensitivity [14]. The nucleation field H_{n} of the CGC medium increases (in terms of negative values) by 80 – 240 kA/m as compared to that of a simple granular medium, which also determines an increase in the rectangularity of the cycle, while the distribution of the switching field is narrower [16].

When the energy of the wall is very low, CGC media practically behave as exchange coupling granular media. When the wall energy is increased, there appear small clusters of magnetic grains, which leads to a reduction of the correlation length and an increase in the experimentally observed SNR. Although this mechanism is capable of producing an important increase in SNR, at high data rates, it can be still limited by the dynamics of the wall, while the track density is limited by the interaction between adjacent tracks.

The parameters of the CGC media can be modeled so that both thermal stability and SNR are improved. The properties of the C layer can be adapted by adopting multilayer structures. On the contrary, it is difficult to reduce and control the exchange interactions in the G layer by means of segregation without sacrificing its anisotropy. This drawback can be overcome by using a G monolayer of decoupled superparamagnetic nanoparticles, self-assembled [19], which would reduce the magnetic interactions that inhibit the self-ordering of the magnetic arrays.

There has been a series of recording simulations on CGC media (see [16] for a presentation of the latest results) in order to figure out the possible mechanisms and solutions for the reduction of noise. Also, the optimised SNR has been compared to the intergranular exchange interactions for high-density granular media, as well as for CGC media.

4. Conclusions

In this review paper, two types of perpendicular recording media, recently proposed, are analysed from the viewpoint of their physical and recording performance.

The first type, the composite media, is a granular recording media, each grain being made up of a magnetically soft part and a magnetically hard one. Its recording potential is comparable to that of tilted magnetic media, but it is more easier to fabricate. Adjusting the volumes, the magnetisations and the anisotropy constants of the two parts can optimise the recording performance. Other advantages of the composite media are their marked insensitivity to the easy axis distribution, a better thermal stability, and much higher recording densities.

The basic principle of the second type, the coupled granular/continuous media, made up of a continuous layer C exchange coupled with a perpendicular granular layer G, is that the small grains of the G layer provide dense pinning centres for the walls in the C layer, thus improving the thermal stability and increasing the SNR. Both thermal stability and SNR can be improved by adjusting the structure and the parameters of the CGC media. Thus, the properties of the C layer can be adapted and improved by adopting some multilayer structures. On the contrary, it is difficult to reduce and control the exchange reactions in the G layer by means of segregation without sacrificing its anisotropy. This drawback can be overcome by using a granular monolayer of decoupled superparamagnetic nanoparticles, which would reduce the magnetic interactions that inhibit the self-ordering of the magnetic arrays.

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*Corresponding author: hgavrila@mct.ro