

This is a repository copy of *Hybrid Design for Advanced Magnetic Recording Media: Combining Exchange-Coupled Composite Media with Coupled Granular Continuous Media*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/121470/>

Version: Accepted Version

---

**Article:**

Chureemart, P., Evans, R. F.L. [orcid.org/0000-0002-2378-8203](https://orcid.org/0000-0002-2378-8203), Chantrell, R. W. [orcid.org/0000-0001-5410-5615](https://orcid.org/0000-0001-5410-5615) et al. (4 more authors) (2017) Hybrid Design for Advanced Magnetic Recording Media: Combining Exchange-Coupled Composite Media with Coupled Granular Continuous Media. *Physical Review Applied*. 024016.

<https://doi.org/10.1103/PhysRevApplied.8.024016>

---

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

# Hybrid design for advanced magnetic recording media: Combining exchange-coupled composite media with coupled granular continuous media

P. Chureemart,<sup>1</sup> R. F. L. Evans,<sup>2</sup> R. W. Chantrell,<sup>2</sup> Pin-Wei Huang,<sup>3</sup> Kangkang Wang,<sup>3</sup> Ganping Ju,<sup>3</sup> and J. Chureemart<sup>1,\*</sup>

<sup>1</sup>Computational and Experimental Magnetism Group, Department of Physics, Mahasarakham University, Mahasarakham, 44150, Thailand

<sup>2</sup>Department of Physics, University of York, York, YO10 5DD, United Kingdom

<sup>3</sup>Seagate Technology, Fremont, CA, USA

(Dated: July 20, 2017)

In order to enhance the performance of advanced granular recording media and understand the physics behind the mechanism of the reversal process, an atomistic spin dynamics simulation is used to investigate theoretically the magnetic properties and the magnetization reversal behaviour for a composite media design. This model allows to investigate the effect of the magnetostatic interaction and inter/intra layer exchange coupling for realistic system. The composite granular medium investigated consists of hard and soft composite layers in which the grains are well segregated with a continuous layer capping layer deposited to provide uniform exchange coupling. We present a detailed calculation aimed at revealing the reversal mechanism. In particular, the angular dependence of the critical field is investigated to understand the switching process. The calculations show a complex reversal mechanism driven by the magnetostatic interaction. It is also demonstrated, at high sweep rates consistent with the recording process, that thermal effects lead to a significant and irreducible contribution to the switching field distribution.

## I. INTRODUCTION

Hard disc drives with high areal density and the low cost are a significant requirement in the marketplace. It is a technical and scientific challenge for hard drive technology. In order to achieve the required high capacity, the key factor to fulfil this aim is the reduction of the grain size as much as possible ( $D < 7$  nm [1–5]) while sustaining a sufficiently large signal to noise ratio (SNR) and thermal stability of written information withstanding the demagnetizing field for 10 years [6]. This leads to the criterion  $K_U V \geq 60 k_B T$ , where  $K_U$  is the uniaxial anisotropy constant,  $V$  is the grain volume,  $k_B$  is Boltzmann's constant and  $T$  is the temperature. The increasing values of  $K_U$  cause the writability of information to become an issue and the conflicting requirements of stability, writability and SNR has become known as the media-trilemma [7].

There are several alternative approaches to overcome these limitations such as heat-assisted magnetic recording (HAMR) [8]; a technology based on using a laser-delivered heat assist for the writing process on very high anisotropy materials i.e. FePt alloys [1, 9, 10]. Moreover, bit patterned media (BPM) [11] and microwave assisted magnetic recording (MAMR) [12] technologies have been also proposed as key ideas. Unfortunately, there are several limitations of these novel technologies which are not only a new design of write head but also the nano fabrication process for industry. Therefore, new designs of conventional perpendicular recording media (PRM) are still the favoured option and perpendicular magnetic record-

ing remains the only technology currently used in hard disk drive.

Conventional PRM have faced several problems mainly on writability and SNR when the grain size decreases, requiring increasingly large values of  $K_U$ . In order to address these problems, there are two main composite media proposed. The first is exchange coupled composite (ECC) media [13, 14] consisting of a low anisotropy material which is known as the switching layer overlaid on a granular high anisotropy layer to reduce the switching field,  $H_S$  via the magnetization reversal mechanism. The second is coupled granular continuous (CGC) media [15–17] introducing the continuous layer to control inter granular exchange coupling which can enhance the performance of medium for high thermal stability and SNR.

Recently, a new design of hybrid granular recording media [18–20] has been introduced, combining the advantages of ECC and CGC (ECC/CGC) media to improve the performance of recording media in order to achieve an areal density beyond 1 Tbit/in<sup>2</sup> in conventional perpendicular recording. The stacked structure of the design consists of a trilayer system comprising a hard layer,  $M_{L1}$  (very high  $K_U$ ), a soft layer,  $M_{L2}$  and a continuous layer,  $M_{L3}$  as a capping layer. The medium comprises small columnar grains which are completely segregated by SiO<sub>2</sub> while the continuous capping layer provides a highly uniform exchange coupling. The key advantages of the magnetic multi-layer design are the high reduction of the switching field due to the presence of the ultra-thin magnetic soft layer leading to dramatically improved writing efficiency and thermal stability. Moreover, the design features of continuous capping layer has a significant advantage by creating a strong pinning to achieve the narrow switching field distribution. In

---

\* jessada.c@msu.ac.th

order to deeper understand the magnetization reversal mechanisms behind the complex structure of PRM, the impact of the exchange coupling among the individual magnetic thin layers affecting to the reversal process and magnetic performance of the whole structure need to expose. Certainly, it is difficult to discover experimentally the detailed reversal processes of each layer in ultra-thin magnetic film. Therefore, the atomistic spin simulation can describe the information on the magnetization reversal process of each layer including the effect of intra/inter exchange coupling at atomic level and also the demagnetizing field which are significant factors for perpendicular complex recording media. The effect of the magnetic parameters such as the uniaxial anisotropy, the atomic exchange interaction and film thickness on magnetic properties of recording media can be studied. Meanwhile, the experimental work do suffers to control these parameters. Atomistic model is the worth tool to investigate the factors affecting the performance of recording media before looking at the detail experimentally.

In previous experimental and theoretical works [21–25], it was reported that the presence of interactions media in granular and ECC media can lead to deviation of the switching behaviour, in particular the angular dependence of magnetic properties, from the coherent Stoner Wohlfarth theory[26]. Studies of the reversal process of such a complex structure as ECC/CGC media are lacking and are still required in experiment and theory. Hence, it is important to investigate the effects of the complicated interaction as the hybrid ECC/CGC media in order to depth understand the complex physics in such new media design. Complex media, with relatively thin layers are not necessarily amenable to micro-magnetic calculations with a relatively crude spatial discretisation. In this paper, atomistic spin simulation[27] based on the Landau-Lifshitz-Gilbert (LLG) equation of motion is chosen to study the complex reversal mechanisms for hybrid ECC/CGC media due to the reduction of magnetic granular grain and the layer thickness almost to the atomic level. It is shown that the quantitative intra/inter exchange coupling between spins becomes very significant in terms of the reversal behaviour. The magnetization curve and the angular dependence of the critical field  $H_{cr}$  are investigated to study the magnetic properties and the reversal process for the complex structure. The effect of time dependence on the switching field, which is significant for the writing process, is also studied in this work. Finally we study the reversal behavior at field sweep rates comparable to those during the recording process. This is shown to give rise to a significant, and irreducible, contribution to the switching field distribution from thermal activation. It is important to note that atomistic model becomes an important tool to investigate the complex behaviour of magnetic nano-materials. It would be very useful for other potential application areas as well. This could be applied for further investigations of complex magnetic structure leading to not only the development of magnetic record-

ing media leading to new media architectures such as heat assisted magnetic recording, bit patterned media and microwave assisted magnetic recording media but also other applications such as the spintronics devices design, spin torque, surface anisotropy in magnetic nanoparticles, the exchange bias in spin valve of read element and the interface effect of nanomangetic devices.

## II. ATOMISTIC MODEL

An atomistic spin dynamic model based on the Landau-Lifshitz-Gilbert (LLG) approach is used to investigate theoretically the magnetic properties of the ECC/CGC medium, including the angular dependence of the critical field ( $H_{cr}$ ) and the magnetization reversal process for the advanced perpendicular recording media (PRM). The energy of the system is described by a classical spin Hamiltonian with the parameters of the CoPt-based alloys commonly used as PRM. The spin Hamiltonian with the Heisenberg form of exchange is written for spin  $i$  as

$$\mathcal{H} = \mathcal{H}_{exc} + \mathcal{H}_{ani} + \mathcal{H}_{app} \quad (1)$$

where,  $\mathcal{H}_{exc}$  is the exchange energy which is written in Heisenberg form as  $\sum_{j \neq i} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$ .  $J_{ij}$  is the exchange coupling between the spin  $i$  and  $j$ , the sum running over nearest neighbors, and  $\mathbf{S}_i$ ,  $\mathbf{S}_j$  is the local normalized spin moment on sites  $i$  and  $j$  respectively.  $\mathcal{H}_{ani}$  is the uniaxial magnetic anisotropy energy expressed as  $k_U (\mathbf{S}_i \cdot \mathbf{e})^2$  where  $k_U$  is the uniaxial anisotropy constant per spin and  $\mathbf{e}$  is the unit vector of the easy axis orientation. The last term of equation 1 is the energy of an external applied magnetic field which is simply given by  $-\mu_s \mathbf{S}_i \cdot \mathbf{H}_{app}$  where  $|\mu_s|$  is the magnitude of the spin moment and  $\mathbf{H}_{app}$  is the external applied field. It is noted that the spin Hamiltonian ( $\mathcal{H}$ ) is expressed as energies per atom and used to determine a field contribution at site  $i$ ,  $H_i = -\partial \mathcal{H} / \partial \mu_i$ , where  $\mu_i$  is the moment on site  $i$ . Furthermore, the thermal fluctuation field  $\mathbf{H}_{ther}$  is included by using Langevin dynamics in the formalism of Brown [28], converting the LLG into the (stochastic) Langevin equation of the problem. Finally, the dipolar field  $\mathbf{H}_{dip}$  is also taken into account in the atomistic model by using a macrocell technique developed by Boerner *et.al.* [29]. The dipolar field is estimated by dividing the system into macrocells. The demagnetization field within each macrocell  $p$  of moment  $\mathbf{m}_{mc}^q$  is given by

$$\mathbf{H}_{demag}^{mc,p} = \frac{\mu_0}{4\pi} \left( \sum_{q \neq p} \frac{3(\mathbf{m}_{mc}^q \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{m}_{mc}^q}{r^3} \right) - \frac{\mu_0}{3} \frac{\mathbf{m}_{mc}^p}{V_{mc}^p} \quad (2)$$

where  $r$  is the separation between dipoles  $p$  and  $q$ ,  $\hat{\mathbf{r}}$  is a unit vector in the direction  $p \rightarrow q$ , and  $V_{mc}^p$  is the volume of the macrocell  $p$ . The first term in Eq. 2 is the usual dipole term arising from all other macrocells in the system, while the second term is the self-demagnetization

field of the macrocell, taken here as having a demagnetization factor  $1/3$ . Further detail of  $\mathbf{H}_{\text{ther}}$  and  $\mathbf{H}_{\text{dip}}$  calculations can be seen in Ref. 27 and 30. Finally, the total field or the net effective local field  $\mathbf{H}_{\text{eff}}^i$  acting on each spin is the summation of the negative first derivative of the spin Hamiltonian including the effect of the thermal field and dipolar field expressed as

$$\mathbf{H}_{\text{eff}}^i = -\frac{1}{\mu_s} \frac{\partial \mathcal{H}}{\partial \mathbf{S}_i} + \mathbf{H}_{\text{dip}} + \mathbf{H}_{\text{ther}} \quad (3)$$

The dynamic motion of magnetization in advanced PRM at atomic level is determined by using a Landau-Lifshitz-Gilbert (LLG) approach. This equation consists of the precessional term of the normalized spin moment around the effective field and the spin relaxation term which is controlled by the damping parameter  $\alpha$  in the damping term of the LLG equation, which is given by

$$\frac{\partial \mathbf{S}_i}{\partial t} = -\frac{\gamma}{(1+\lambda^2)} [\mathbf{S}_i \times \mathbf{H}_{\text{eff}}^i + \lambda \mathbf{S}_i \times (\mathbf{S}_i \times \mathbf{H}_{\text{eff}}^i)] \quad (4)$$

where  $\mathbf{S}_i$  is the unit vector of the spin moment  $i$  to represent the direction of spin,  $\gamma$  is the gyromagnetic ratio and  $\lambda$  is the Gilbert damping constant which is used at 1.0 for this system. we note that all atomic simulations are done using the VAMPIRE software package [27]

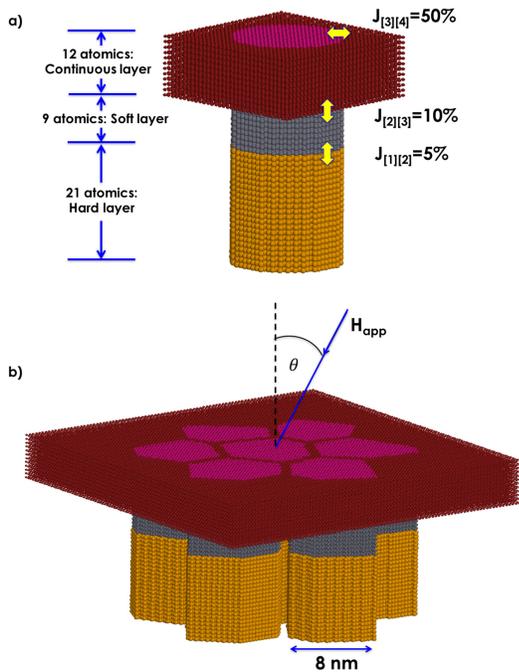


FIG. 1. a) a single grain structure b) the few grains structure for advanced media design

### III. ECC/CGC RECORDING MEDIA DESIGN

The structure of the ECC/CGC recording medium is designed with a trilayer system to drive a high areal density beyond 1TB per square inch with a high anisotropy constant ( $H_k$ ) and small grains. The aim is to achieve a medium with reduced coercivity whilst minimizing the reduction of the zero-field energy barrier responsible for long-term stability. The details of material parameters used in our atomistic spin dynamic calculation are determined experimentally for the future granular recording media which are provided by Seagate Technology of Fremont. Due to this calculation based on the spin Hamiltonian shown as equation 1, the magnetic parameters such as anisotropy constant  $k_U$ , saturation magnetization and exchange inter/intra layer coupling are necessary to parameterize in term of atomic level. The trilayer media design consists of: a storage layer with a high anisotropy field,  $H_{k1}$  of 22 kOe, the uniaxial anisotropy constant  $k_{U1} = 5 \times 10^{-23}$  J/atom, saturation magnetization  $M_s = 4.4\mu_B$  (700 emu/cc) and a thickness of 21 atomic layers ( $\sim 7\text{nm}$ ). The second layer is a softer layer with a lower  $H_{k2}$  of 16 kOe,  $k_{U2} = 4.2 \times 10^{-23}$  J/atom,  $M_s = 5\mu_B$  (800 emu/cc) and a thickness of 9 atomic layers ( $\sim 3\text{nm}$ ). The third layer is the continuous layer capping the granular medium having the lowest  $H_{k3}$  of 10 kOe,  $k_{U3} = 2 \times 10^{-23}$  J/atom,  $M_s = 3.8\mu_B$  (600 emu/cc) and a thickness of 12 atomic layers ( $\sim 4\text{nm}$ ). It is noted that our magnetic parameters used in this work agree well with the previous experimental works for future granular recording media with HAMR and MAMR technologies reported by Shin Saito et al. [31] and Kim Kong Tham et al. [32, 33]

The composite materials for all layers are based on a common CoPt-based alloy with the Curie temperature of 1000 K. The grain size of the first and second layers is set as 8 nm with wide non-magnetic grain boundaries of 1 nm in order to remove the inter granular exchange coupling. The top layer is modelled as a continuous film with no grain boundaries in which the exchange intralayer coupling is set at 50% of  $J_{ij}$  where  $J_{ij}$  is the exchange coupling strength between atoms  $J_{ij} = 9.86 \times 10^{-21}$  J/link. Meanwhile, the exchange interlayer coupling strength between first and second layers, second and third layers is set 5% and 10% of  $J_{ij}$  respectively. Figure 1 a) and b) present a visualisation of the atomic structure of a single grain ( $\sim 23000$  atoms) and few grains ( $\sim 175000$  atoms) with 1.0 nm spacing respectively employed to examine the impact of media architectures on the magnetization reversal process and the angular dependent critical field.

### IV. MAGNETIC CHARACTERIZATION

We present an investigation of the magnetic properties of hybrid ECC/CGC media, firstly showing the basic hysteretic behavior. In the following magnetic properties are calculated using the atomic model for two cases: firstly a small system comprising 7 grains using  $34 \times 34 \times 16 \text{ nm}^3$

system as figure 1 b) and secondly a multi-grain structure using  $50 \times 50 \times 16 \text{ nm}^3$  system containing 27 grains.

In order to investigate the magnetic properties of ECC/CGC composite media, we first show a typical hysteresis loop for the small system at an angle between the applied field and the normal direction to the film plane  $\theta = 0^\circ$ . Hysteresis loops were calculated for a reversal time of 20 ns. The impacts of the dipolar field and thermal activation are investigated. Figure 2 shows the normalized hysteresis loops with and without the dipolar field at 0 K for the ECC/CGC medium described earlier. It is clear that the  $\mathbf{H}_{\text{dip}}$  has a significant effect on the magnetic properties especially the coercivity  $H_c$ . The value of  $H_c$  reduces significantly from 15 kOe to 10 kOe on inclusion of the dipolar field. The result shows the strong impact of dipolar field on coercivity due to the effect of the large demagnetizing field reversing the continuous layer for ECC/CGC structure. The reduction essentially arises from the onset of a nucleation/propagation mechanism driven by the dipolar field. This will be investigated shortly in detail with the comparative visualisation of the reversal process with and without  $\mathbf{H}_{\text{dip}}$ .

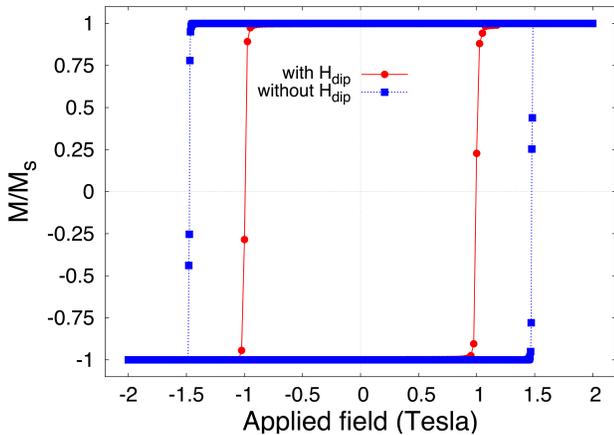


FIG. 2. Hysteresis loops of a single grain structure with and without dipolar interaction showing the dipole field gives rise to a significant reduction in coercivity.

Moreover, the composite design of the trilayer structure can improve the performance of recording media as expected. The hysteresis loop in Fig. 2 shows a significant reduction of the switching field to a value of  $H_c$  of 10 kOe while the  $H_k$  of the hard or storage layer is a very high value of 22 kOe. The results also indicate the effect of parameters used in the model. The reduction of  $H_c$  is probably due to the presence of the softer layer with a low anisotropy constant and a low exchange interlayer coupling (5% of  $J_{ij}$ ). Moreover, the shape of hysteresis loop is very square due to the presence of the third layer with a strong intralayer coupling strength (50% of  $J_{ij}$ ). This, coupled with the effects of the saturation magnetization and anisotropy of the layers means that a complete optimization of the media properties is beyond the scope of the current work. Optimization of the properties is

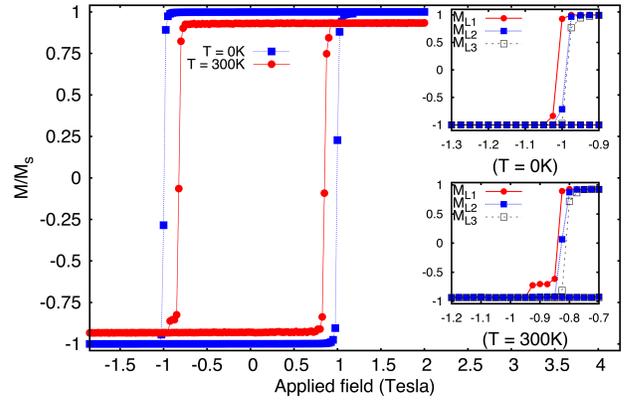


FIG. 3. Hysteresis loop measured at 0 degrees with  $\mathbf{H}_{\text{dip}}$  and calculated with a reversal time of 20 ns at the different temperature. The insets show the magnetization curve of each magnetic layer around the  $H_S$  at  $T = 0$  (top) and 300 K (bottom)

probably best done by using the atomistic approach to parameterize simplified models, possibly with one spin per layer, in order to lower the computational cost. Here we concentrate on developing an understanding of the basic reversal mechanisms involved, including the effects of interactions, of which an investigation follows.

We now turn to the set of interacting grains. Initial hysteresis loop calculations are made using the small system of 7 grains; this is due to the necessity of long run times to achieve equilibrium loops. Fig. 3 shows the impact of thermal activation at 300 K on the loops and coercivity in comparison with the 0 K behavior with the reversal of each individual layer as an inset. The thermal energy directly reduces the value of coercivity and the saturation magnetization of the whole system. However it does not affect the form of the hysteresis loop, which remains very square in both cases. Moreover, information on the magnetization reversal process can be obtained from the net magnetization curve of each layer. The insets of Fig.3 show the layer resolved magnetization behavior as  $M_{L1}$  (hard layer),  $M_{L2}$  (soft layer) and  $M_{L3}$  (continuous layer) around the switching state at a field  $H_S$  and temperature of 0 K (top) and 300 K (bottom). The results for the both temperature display similar behavior. The  $H_S$  of  $M_{L1}$  layer is the highest value while the  $H_S$  of  $M_{L2}$  is slightly higher than the top layer,  $M_{L3}$  at the reversal state. This indicates that the reversal process probably initiates in the top layer and propagates to through the bottom layer. This is confirmed by the visualisation of the switching process at atomic level as shown in figure 4 I) and II), where the nucleation and propagation can clearly be seen. An interesting feature of the inset of Fig.3 is the step in magnetization observable close to saturation in the negative- going loop at  $T = 300 \text{ K}$ . This is associated with the late switching of one of the grains due to stabilisation of the positively oriented grain by the magnetostatic field.

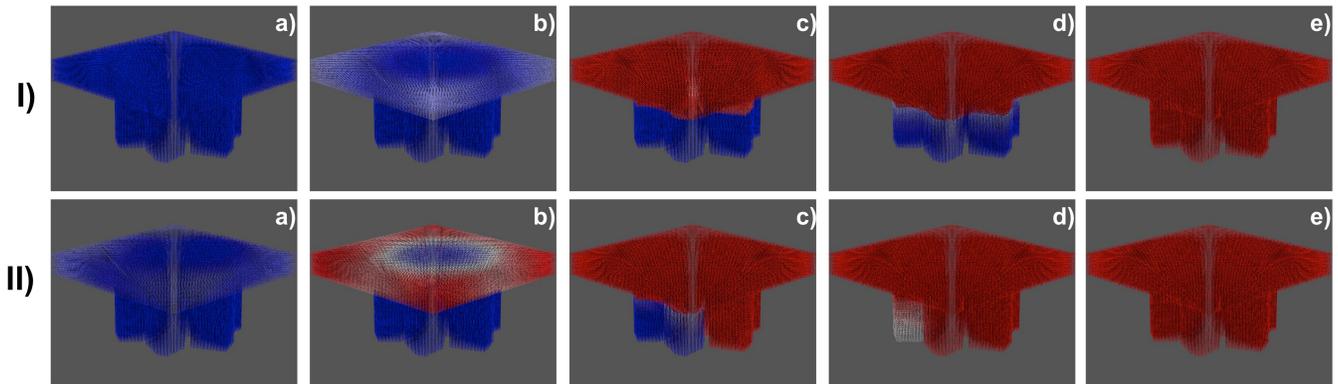


FIG. 4. Visualisation of atomic magnetization reversal for the few grains system at  $T=0\text{K}$  and  $0\text{ deg}$  for exclusion of  $\mathbf{H}_{\text{dip}}$  (I. a-e) and inclusion of  $\mathbf{H}_{\text{dip}}$  (II. a-e)

The effect of the magnetostatic interaction field on the reversal behaviour for hybrid ECC/CGC media referred to earlier is further investigated by observation of the atomistic reversal process for the few grain system. Figure 4 (I) and II) display visualizations of the atomistic reversal process for exclusion and inclusion of the magnetostatic field respectively at  $0\text{ K}$ . For the exclusion of  $\mathbf{H}_{\text{dip}}$  case, figures 4 (I. a-e) show the subsequent reversal process of each layer. The top layer initially reverses when the applied field is higher than  $H_{\text{K3}}$ . Subsequently, the whole stack of continuous layer and soft layer reverse followed finally by the hard layer. For the case including  $\mathbf{H}_{\text{dip}}$  as shown in Fig. 4 (II. a-e), it is clearly seen that the partial region of the top layer reverses initially. This is due to the strong effect of the dipolar field to initiate a collective nucleation and propagation mechanism especially on a continuous layer having a high exchange coupling interaction. The reversal of spins is transmitted to neighbouring spins leading to the reversal of all grains almost simultaneously. This may cause the reduction of the coercivity and confirms that the dipolar field becomes an important factor for the magnetic properties of complex recording media. We note that figure 4 shows a subtle effect of the magnetostatic field on the reversal mechanism. Comparison between figures 4 (I) and 4 (II) shows that the reversal is much more uniform in the absence of the magnetostatic field. Figure 4 (I) shows similar time propagation of reversal in each of the grains, whereas 4 (II) shows that individual grains switch at different times. This is an effect which we attribute to spatial variations of the magnetostatic field arising from slight differences in the grain morphology, and which could contribute to the width of the thermal SFD to be described later.

## V. ANGULAR DEPENDENCE OF $H_{\text{cr}}$

One of the main aims of this work is to understand the switching behaviour of the multilayer structure. The inclusion of the magnetostatic interaction field is taken into account in the atomistic calculation to demonstrate

its significant effect on the magnetic properties. The angular dependence of the critical field,  $H_{\text{cr}}$  defined as the field at which the magnetization flips irreversibly from one stable state to another is used to investigate the reversal process. The influence of thermal effects at room temperature  $300\text{ K}$  is modelled by including the thermal fluctuation field,  $H_{\text{ther}}$ . In this atomistic calculation, the magnetic properties of each layer such as magneto crystalline anisotropy field, layer thickness, grain diameter and exchange inter/intra layer coupling are given in section III. All calculations were done for the small (7 grain) system.

The normalized hysteresis loop is calculated as a function of  $\theta$  ranging from  $0^\circ$  to  $90^\circ$  with the field step of  $5^\circ$  in order to explore  $H_{\text{cr}}$ . The angular dependence of the critical field is calculated with and without magnetostatic interactions at temperatures of  $0\text{ K}$  and  $300\text{ K}$ . Figure 5 a) and b) demonstrate typical hysteresis loops at  $0\text{ K}$  for the angular ranges  $0^\circ$  to  $45^\circ$  and  $50^\circ$  to  $90^\circ$  respectively. Loops were calculated for a reversal time of  $20\text{ ns}$ . The results show that the  $H_{\text{cr}}$  has a maximum value at  $0^\circ$  and reduces to a minimum value with increasing angle at  $45^\circ$ . Subsequently, the critical field increases as the angle approaches  $90^\circ$ . It is interesting to note that hysteresis loops without  $H_{\text{dip}}$  for large angles display the crossover effect resulting from irreversible switching between minima as shown in Fig.5 b). This feature and the general form of the switching behavior suggests that in the absence of magnetostatic interaction the magnetization reverses coherently as Stoner Wohlfarth behaviour [26] as observed and reported by Tannous and Gieraltowski [34].

Calculations of the  $H_{\text{cr}}(\theta)$  normalized by  $H_{\text{cr}}(\theta=0)$  as a function of the applied field angle  $\theta$  were performed at  $0\text{ K}$  and  $300\text{ K}$  to determine the magnetization reversal mechanism. In order to investigate the effects of magnetostatic interaction field and thermal activation on the switching process, the comparison of the variation of the normalized  $H_{\text{cr}}(\theta)/H_{\text{cr}}(0)$  with angle are shown in Fig. 6 for calculations with and without the magnetostatic interaction field.

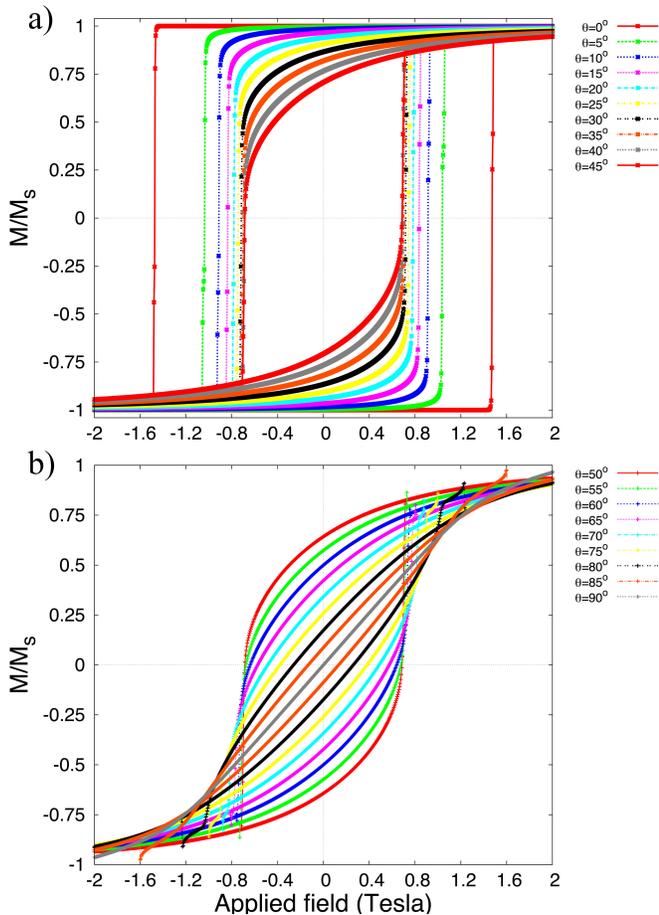


FIG. 5. The typical hysteresis loops at 0 K calculated for a reversal time of 20 ns without the inclusion of magnetostatic interactions: (a) the angular ranges from 0 to 45 degrees and (b) from 50 to 90 degrees

Figure 6 a) shows the angular dependence of  $H_{cr}$  for the non-interacting case for both temperatures. It is clearly observed that the minimum of critical field is close to half of  $H_{cr}(0)$  value at  $45^\circ$  for absolute both temperatures. The change of the normalised  $H_{cr}$  with the angle shows the similar behaviour with the Stoner Wohlfarth theory [26], also included in Fig. 6 a), for both temperatures which is a good indication of coherent magnetization reversal for the system without magnetostatic fields. Further evidence can be observed from the visualisation of atomic reversal process given in Fig. 4 (I. a-e). However, coherent reversal behaviour is not expected to occur in such a complex structure[23, 24], suggesting that non-coherent behaviour is induced by magnetostatic interactions.

We now proceed to investigate the angular dependence of  $H_{cr}$  for more realistic calculations by including the effect of the magnetostatic interaction field into the system. Interestingly, it is found that the inclusion of interactions strongly influences the reversal mechanism of

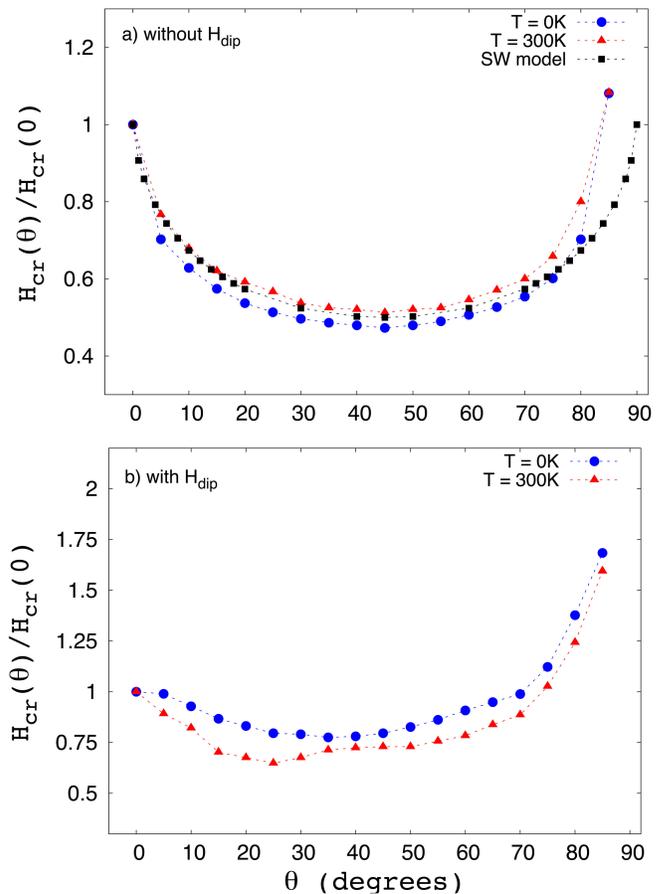


FIG. 6. Variation of the normalized critical field,  $H_{cr}(\theta)/H_{cr}(0)$  as a function of angle and temperature (0 K and 300 K): (a) no  $H_{dip}$  effect and (b) including  $H_{dip}$  effect

the ECC/CGC media observed from the transformation of the variation of  $H_{cr}$  in figure 6 b). The trend of angular dependence for both temperatures shows that the reversal behaviour clearly deviates from coherent Stoner Wohlfarth theory[26]. The curve is asymmetric with minimum critical field at  $35^\circ$  and  $25^\circ$  for  $T = 0 K$  and  $300 K$  respectively. The form of the variation is closer to that characteristic of domain wall motion initiated and driven by the magnetostatic interaction.

The trend of variation of  $H_{cr}$  with angle demonstrates the incoherent magnetization reversal during the switching process. The incoherent reversal causes the appearance of several reversal modes such as cooperative reversal between grains, collective nucleation and propagation and pinning at the interface layer due to the lateral exchange interaction. This can be clearly seen in Fig. 4(II. a-e). The continuous layer starts to reverse as an incoherent reversal process. The continuous layer initiates a collective domain wall nucleation due to the strong exchange between layers. magnetization reversal in the granular layer cannot occur until the domain wall propa-

gates through the bottom as Fig.4(II. c-e). This reversal behaviour is completely different to the Stoner Wohlfarth (S-W) model [26]. Significantly, the results confirm that the magnetostatic interaction effect is the crucial factor driving the reversal behaviour for complicated advanced recording media in simulation which cannot be neglected.

Figure 6 must be considered alongside the nature of the switching as illustrated by the transient magnetization configurations shown in Fig. 4. Figure 6 (a) apparently shows classic S-W behaviour: however, inspection of Fig. 4 (I) shows that reversal proceeds by nucleation and propagation. A possible interpretation of this is that nucleation involves a similar form of energy barrier to the S-W model. Investigation of this prospect would be interesting, but would require the calculation of energy barriers using the constrained Monte-Carlo method [35], which is beyond the scope of the current work. As expected, the magnetostatic field has a strong bearing on the reversal mechanism. Figure 6 (b) shows an angular variation consistent with domain wall nucleation and propagation. However, as noted earlier, the transient states shown in Fig. 4 (II) show individual grain reversal at different times. It seems likely that this is an important contribution to the thermal SFD considered shortly.

Moreover, our angular dependence calculations are agree well with the previous experimental works which observed the irreversible behaviour for advanced recording media. The variation of  $H_{cr}$  technique was used by Saharan et.al. [23, 24] to study the magnetization reversal behaviour in tri-layer structure based on exchange spring media [13] separated with the additional interface layer. They found that the minimum angle of the critical field is about  $30^\circ - 35^\circ$  which is consistent with our calculations for hybrid media design including magnetostatic field case. The similar trend of variation of  $H_{cr}$  with angle of the segregated granular recording based on CoCrPt-SiO<sub>2</sub> media is also observed experimentally by Morrison et.al.[25]. They found that asymmetry of variation of the critical field and the breakdown of Stoner-Wohlfarth behaviour occurred in cases of strong magnetostatic field and weak exchange coupling.

## VI. TIME DEPENDENCE OF $H_c$ IN ECC/CGC MEDIA

A critical parameter in advanced recording media is the switching field of the medium. The significant feature of this field is the time or frequency dependence of switching field described by the well known Sharrock equation [36, 37] as

$$H_c(t) = H_K \left[ 1 - \left( \frac{k_B T}{K_U V} \ln \left( \frac{f_0 t}{0.693} \right) \right)^n \right] \quad (5)$$

where  $H_c(t)$  is the time dependence of the coercivity,  $t$  is the time scale,  $H_K$  is the anisotropy field and  $f_0$  is a frequency factor. From the Sharrock equation, short time scales give rise to large values of the switching field. Of particular importance is the fact that the writing process

operates at extremely high frequency (GHz) or short time scale ( $< 10$  ns)[37]. Consequently the write field must be larger than the switching field at the write frequency.

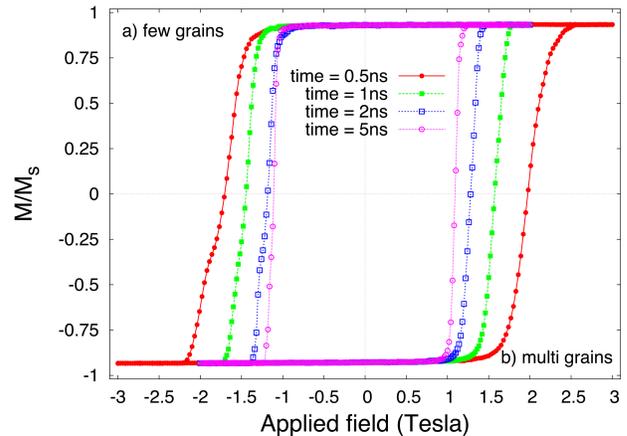


FIG. 7. Half hysteresis loop a) few grains system (half left) and b) multi grains system (half right) as a function of the different loop time 0.5 ns, 1 ns, 2 ns and 5 ns at 300 K

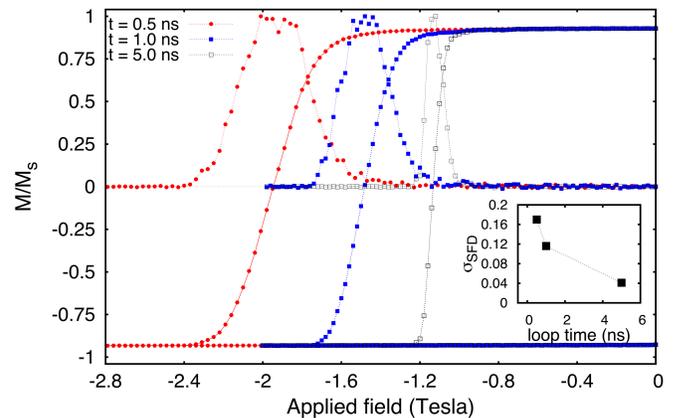


FIG. 8. Switching field distribution obtained at the different loop time 0.5 ns, 1 ns and 5.0 ns by differentiation of the hysteresis loop and the inset shows the SFD width  $\sigma_{SFD}$  versus loop times.

The time dependence of  $H_c$  is investigated for both small and multi-grain systems as a function of the different loop time at 0.5 ns, 1 ns, 2 ns and 5 ns with the external field applied normal to the plane at 300 K. The aim of this investigation is to study the properties of the system in the transition region into the sub-ns timescale of magnetic recording. In particular we are interested in the form of the hysteresis loop and also the thermal SFD [38] which represents an irreducible minimum SFD for the system. For computational efficiency the small system was used for initial investigations and the multi-grain structure used for the detailed calculations of the thermal switching field distribution described later.

Figure 7 a) and b) show half (left) hysteresis loop for

the small system and half (right) hysteresis loop for multi grains system at the different loop time respectively. The results for both system exhibit the expected significant reduction of coercivity with increasing loop time which is consistent with the Sharrock equation. The value of  $H_c$  is similar at each loop time for both systems. There is an obvious kink in the magnetization curve at a short loop time for the 7 grain system, which disappears for multi grains system due to more statistical data. The feature arises from the tendency noted earlier for delayed switching of some grains; it leads to a kink in the small system but a smooth magnetization curve for the multi-grain case.

Finally, the switching field distribution (SFD) is calculated from the gradient of the magnetization curve and presented for the different loop times in figure 8. The results show that reduction of the loop time significantly increases the SFD. According to the the SFD width ( $\sigma_{\text{SFD}}$ ), the inset of figure 8 shows the decreasing of  $\sigma_{\text{SFD}}$  with the increasing of the loop time. This effect arises from the reduction of the energy barrier at which switching occurs for small reversal times [38] which broadens the field dependence of the switching probability.

## VII. CONCLUSION

In this work, we have performed atomistic calculations based on the Landau-Lifshitz-Gilbert equation of motion to study the magnetic properties and the magnetization reversal behaviour of the composite trilayers system as advanced recording media. The new design of hybrid

granular recording media[18–20] has been introduced using the advantage of ECC and CGC media. The structure of medium consists of trilayers system as hard layer, soft layer and continuous layer. From magnetic characterisation, the hybrid ECC/CGC media demonstrated the enhancements of the recording performance such as thermal stability and SNR by reducing of switching field and narrowing of the switching field distribution.

The variation of the critical field as a function of applied field angle was investigated to understand the magnetization reversal mechanism. We have also reported a significant effect of the magnetostatic interaction field on the simulation. The inclusion of  $H_{\text{dip}}$  was taken into account the atomistic calculation to demonstrate its strong effect on reversal process of realistic system. The feature of angular dependence of  $H_{\text{cr}}$  without the effect of  $H_{\text{dip}}$  showed the coherent reversal behaviour like a Stoner Wohlfarth model[26] which does not describe the mechanism of a complex structure. Meanwhile, the calculations including the effect of  $H_{\text{cr}}$  indicate the incoherent reversal process due to the appearance of several complex reversal modes. Therefore, it confirms that the magnetostatic interaction field is a crucial factor which cannot be neglected for simulations to reveal a realistic properties.

## ACKNOWLEDGMENTS

J.C. gratefully acknowledges financial support from Division of Research, Mahasarakham University, Thailand and DPST Research Grant No:23/2557.

- 
- [1] S. Piramanayagam and K. Srinivasan, Recording media research for future hard disk drives, *J. Magn. Mater.* 321, 485 (2009).
  - [2] J. Chureemart, P. Chureemart, R. Evans, R. W. Chantrell, and K. O'Grady, Magnetic orientation in advanced recording media, *J. Phys. D: Appl. Phys.* 44, 455002 (2011).
  - [3] J. Chureemart, L. Lari, T. P. Nolan, and K. O'Grady, The effect of SiO<sub>2</sub> content on activation volumes in exchange coupled composite media, *J. Appl. Phys.* 114, 083907 (2013).
  - [4] V. Mehta, T. Wang, Y. Ikeda, K. Takano, B. D. Terris, B. Wu, C. Graves, H. A. Durr, A. Scherz, J. Stohr, and O. Hellwig, Extracting magnetic cluster size and its distributions in advanced perpendicular recording media with shrinking grain size using small angle x-ray scattering, *Appl. Phys. Lett.* 114, 202403 (2015).
  - [5] C. Papusoi, M. Desai, and R. Acharya, Evaluation of intergranular exchange coupling and magnetic domain size in coCrPt/SiO<sub>2</sub> thin films with perpendicular anisotropy, *J. Phys. D: Appl. Phys.* 48, 215005 (2015).
  - [6] S. Charap, P.-L. Lu, and Y. He, Thermal stability of recorded information at high densities, *IEEE Trans. Magn.* 33, 978 (1997).
  - [7] H. J. Richter, The transition from longitudinal to perpendicular recording, *J. Phys. D: Appl. Phys.* 40, R149 (2007).
  - [8] R. Rottmayer, S. Batra, D. Buechel, W. Challener, J. Hohlfield, Y. Kubota, L. Li, B. Lu, C. Mihalcea, K. Mountfield, K. Pelhos, C. Peng, T. Rausch, M. A. Seigler, D. Weller, and X. Yang, Heat-assisted magnetic recording, *IEEE Trans. Magn.* 42, 2417 (2006).
  - [9] D. Weller, O. Mosendz, G. Parker, S. Pisana, and T. S. Santos, L10 FePtXY media for heat-assisted magnetic recording, *Phys. Stat. Solid. A* 210, 1245 (2013).
  - [10] S. Granz, K. Barmak, and M. Kryder, Granular L10 FePt:X (X = Ag, B, C, SiO<sub>x</sub>, TaO<sub>x</sub>) thin films for heat assisted magnetic recording, *Eur. Phys. J. B* 86, 1 (2013).
  - [11] B. D. Terris and T. Thomson, Nanofabricated and self-assembled magnetic structures as data storage media, *J. Phys. D: Appl. Phys.* 38, R199 (2005).
  - [12] J. G. Zhu, X. Zhu, and Y. Tang, Microwave assisted magnetic recording, *IEEE Trans. Magn.* 44, 125 (2008).
  - [13] R. Victora and X. Shen, Composite media for perpendicular magnetic recording, *IEEE Trans. Magn.* 41, 537 (2005).
  - [14] D. Suess, T. Schrefl, S. Fahler, M. Kirschner, G. Hrkcac, F. Dorfbauer, and J. Fidler, Exchange spring media for

- perpendicular recording, *Appl. Phys. Lett.* 87, 012504 (2005).
- [15] Y. Sonobe, D. Weller, Y. Ikeda, M. Schabes, K. Takano, G. Zeltzer, B. Yen, M. E. Best, S. Greaves, H. Muraoka, and Y. Nakamura, Thermal stability and snr of coupled granular/continuous media, *IEEE Trans. Magn.* 37, 1667 (2001).
- [16] G. Choe, M. Zheng, B. R. Acharya, E. N. Abarra, and J. N. Zhou, Perpendicular recording coptero composite media with performance enhancement capping layer, *IEEE Trans. Magn.* 41, 3172 (2005).
- [17] J. Yasumori, Y. Sonobe, S. J. Greaves, and K. K. Tham, Approach to High-Density Recording Using CGC Structure, *IEEE Trans. Magn.* 45, 850 (2009).
- [18] T. P. Nolan, B. F. Valcu, and H. J. Richter, Effect of composite designs on writability and thermal stability of perpendicular recording media, *IEEE Trans. Magn.* 47, 63 (2011).
- [19] K. K. Tham, S. Saito, D. Hasegawa, N. Itagaki, S. Hinata, S. Ishibashi, and M. Takahashi, Effect of inhomogeneous microstructure of granular layer on inter granular/inter layer exchange coupling in stacked perpendicular recording media, *J. Appl. Phys.* 112, 093917 (2012).
- [20] J. Chureemart, P. Chureemart, J. Pressesky, T. Nolan, and K. O'Grady, Media design and orientation in perpendicular media, *IEEE Trans. Magn.* 49, 3592 (2013).
- [21] C. Morrison, L. Saharan, G. Hrkac, T. Schrefl, Y. Ikeda, K. Takano, J. J. Miles, and T. Thomson, Inter/intra granular exchange and thermal activation in nanoscale granular magnetic materials, *Appl. Phys. Lett.* 99, 2011 (2011).
- [22] L. Saharan, C. Morrison, J. J. Miles, T. Thomson, T. Schrefl, and G. Hrkac, Angle dependence of the switching field of recording media at finite temperatures, *J. Appl. Phys.* 110, 103906 (2011).
- [23] L. Saharan, C. Morrison, Y. Ikeda, K. Takano, J. J. Miles, T. Thomson, T. Schrefl, and G. Hrkac, Grain boundaries in granular materials-A fundamental limit for thermal stability, *Appl. Phys. Lett.* 102, 142402 (2013).
- [24] L. Saharan, C. Morrison, J. J. Miles, T. Thomson, T. Schrefl, and G. Hrkac, Modelling interfacial coupling in thin film magnetic exchange springs at finite temperature, *J. Appl. Phys.* 114, 153908 (2013).
- [25] C. Morrison, L. Saharan, Y. Ikeda, K. Takano, G. Hrkac, and T. Thomson, Quantifying exchange coupling in segregated granular materials, *J. Phys. D: Appl. Phys.* 46, 475002 (2013).
- [26] E. C. Stoner and E. P. Wohlfarth, A mechanism of magnetic hysteresis in heterogeneous alloys, *Phil. Trans. R. Soc. Lond.* 240, 599 (1948).
- [27] R. F. L. Evans, W. J. Fan, P. Chureemart, T. a. Ostler, M. O. a. Ellis, and R. W. Chantrell, Atomistic spin model simulations of magnetic nanomaterials., *J. Phys. Condens. Matter* 26, 103202 (2014).
- [28] W. F. Brown, Thermal fluctuations of a single-domain particle, *J. Appl. Phys.* 34, 1319 (1963).
- [29] E. Boerner, O. Chubykalo-Fesenko, O. Mryasov, R. Chantrell, and O. Heinonen, Moving toward an atomistic reader model, *IEEE Trans. Magn.* 41, 936 (2005).
- [30] P. Chureemart, R. F. L. Evans, and R. W. Chantrell, Dynamics of domain wall driven by spin-transfer torque, *Phys. Rev. B* 83, 184416 (2011).
- [31] S. Saito, S. Hinata, and M. Takahashi, Evaluation of atomic layer stacking structure and curie temperature of magnetic films for thermally assisted rrecording media (invited), *IEEE Trans. Magn.* 50, 3201205 (2014).
- [32] K. K. Tham, S. Hinata, S. Saito, and M. Takahashi, Successful fabrication of high  $k_u$  columnar copt-sio<sub>2</sub> granular film sputtered under high substrate temperature, *J. Appl. Phys.* 115, 17B752 (2014).
- [33] K. K. ham, S. Hinata, and S. Saito, Effect of topological bumpy surface underlayer on compositionally modulated atomic layer stacking in high  $k_u$  hcp co<sub>8</sub>opt<sub>2</sub>o film with (00.2) crystallographic texture orientation, *IEEE Trans. Magn.* 51, 3202404 (2015).
- [34] C. Tannous and J. Gieraltowski, The stoner wohlfarth model of ferromagnetism: Static properties, *Eur. J. Phys.* 29, 475 (2008).
- [35] P. Asselin, R. F. L. Evans, J. Barker, R. W. Chantrell, R. Yanes, O. Chubykalo-Fesenko, D. Hinzke, and U. Nowak, Constrained monte carlo method and calculation of the temperature dependence of magnetic anisotropy, *Phys. Rev. B* 82, 054415 (2010).
- [36] M. Sharrock and J. McKinney, Kinetic effects in coercivity measurements, *IEEE Trans. Magn.* 17, 3020 (1981).
- [37] M. P. Sharrock, Time dependence of switching fields in magnetic recording media (invited), *J. Appl. Phys.* 76, 6413 (1994).
- [38] O. Hovorka, R. F. L. Evans, R. W. Chantrell, and A. Berger, Rate-dependence of the switching field distribution in nanoscale granular magnetic materials, *Appl. Phys. Lett.* 97, 062504 (2010).