Continuous/Cluster-Pinned Recording Media

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We propose and theoretically investigate a new class of nanostructured magnetic recording films, cluster-pinned recording media. The films consist of magnetic clusters exchange coupled to a continuous hard layer with perpendicular anisotropy and low coercivity. Our calculations yield the coercivity and the cross-track correlation length as a function of film thickness and pinning density and strength. The mechanism is very similar to the Gaunt–Friedel pinning in bulk magnets, which differs from ordinary strong pinning by the self-consistent dependence of wall curvature and coercivity on defect concentration. The main difference is the exponent for the coercivity as a function of the pinning strength, which is equal to 2 in the bulk but equal to 3/2 in thin films. The pinning strength is estimated for various regimes, and it is shown that the diminished domain-wall curvature reduces jitter.

Index Terms—**Coercivity, domain-wall pinning, magnetic recording.**

I. INTRODUCTION

RECENTLY, coupled granular and continuous (CGC) thin films [1], [2] and percolating particulate magnets [3] have been proposed as recording media. It has been argued that the thermal stability of CGC media is better than that of decoupled granular media [1] and bit transitions in CGC media may be positively affected [4]. However, the determination and control of jitter in pinning-type magnets is a nontrivial issue. This refers not only to the vicinity of the percolation threshold, where the percolating backbone causes the correlation length (jitter) to diverge [5], [6]. Away from the percolation threshold, interaction domains [7], and cooperative effects, introduced by exchange coupled grains, are well known to reduce the coercivity while smoothing bit transitions (zigzag boundaries) and enhancing the slope of the hysteresis loop [8]–[12].

Our cluster-pinned recording media (CPRM) consist of a nearly defect-free continuous thin film with high perpendicular anisotropy, exchange coupled to an adjacent layer of nanoscale high-anisotropy clusters. This system is different from the previously considered CGC media. The small number of defects leads to easy nucleation and domain-wall motion in the continuous film, accompanied by a low coercivity. However, the clusters act as pinning centers and control—together with the thickness t and anisotropy K_1 of the continuous layer—the coercivity, jitter, and other properties of the medium. Fig. 1 compares (a) ordinary strong-pinning media with (b) the present structures. Like soft-magnetic nanostructures [13], the present material is characterized by correlation lengths ξ larger than interparticle distance L. However, unlike the weak pinning in soft-magnetic materials, the present pinning is strong, and the domain wall remains narrow due to the presence of the highly anisotropic continuous layer.

This paper focuses on the coercivity and cross-track correlation length, which reflect the pinning strength of the cluster and the thickness of the continuous layer. An important issue throughout the paper is the distinction between ordinary strong pinning, or Kersten pinning, and Gaunt–Friedel pinning. We
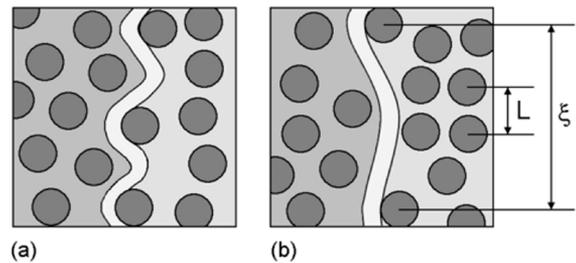
Fig. 1. Pinning-type recording media: (a) ordinary strong or Kersten pinning and (b) Gaunt–Friedel pinning, as considered in this paper.

will see that the latter improves the jitter by reducing the domain-wall curvature.

II. STRONG PINNING MECHANISMS

This paper involves *strong* domain-wall pinning, defined as discrete Barkhausen jumps between individual pinning centers. By comparison, weak pinning means that the simultaneous involvement of many defects. Weak pinning is usually accompanied by small coercivities and large (submicron) length scales [13] and therefore not suitable for high-density recording. There are various types of strong pinning, blending into magnetization reversal in ensembles of weakly interacting Stoner–Wohlfarth particles [12]. Here, we consider moderate to strong interactions, mediated by the continuous thin film.

Ordinary strong pinning, or *Kersten pinning*, is based on the competition between the pinning force $p = \mathrm{d}E_{\mathrm{wall}}/\mathrm{d}x$ and the the Zeeman force $2\mu_{\mathrm{o}}M_{\mathrm{s}}H \, \mathrm{d}V/\mathrm{d}x$ [14], [15]. In thin films, the coercivity is given by

$$H_{\mathrm{o}} = p/\mu_{\mathrm{o}}MLt \tag{1}$$

where L is the average distance between pinning centers. We note that the coercivity (the pinning field) is proportional to the pinning force p, as one might expect on intuitive grounds.

Between pinning centers, the domain walls are curved, with inverse curvature radii $\kappa = \mu_{\mathrm{o}}M_{\mathrm{s}}H/\gamma$ (bulk) and $\kappa = 2\mu_{\mathrm{o}}M_{\mathrm{s}}H/\gamma$ (thin films). However, the coercivity is independent of the curvature, and the lateral correlation length (or cross-track correlation length) ξ is essentially equal to the
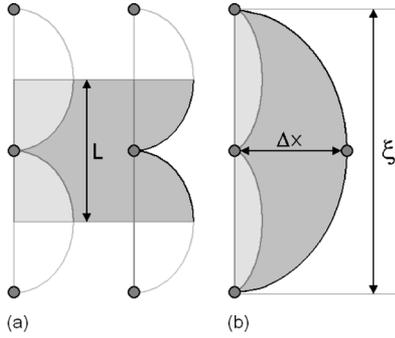
Fig. 2. Pinning and Barkhausen volume: (a) Kersten pinning and (b) Gaunt–Friedel pinning. In (a), the Barkhausen volume (gray area) is proportional to L^3 (bulk) or $L^2 t$ (thin films), whereas in (b), the Barkhausen jump distance Δx must be determined selfconsistently.

Fig. 3. (Solid line) Coercivity and (dashed line) correlation length as a function of film thickness.

average distance L between pinning centers. This is the reason for the zigzag domain walls between interaction domains.

As noted in the context of bulk magnets [16], the Kersten scenario is unrealistic for small domain-wall curvatures, Fig. 1(b). The theory, developed by *Gaunt*, is analogous to an earlier treatment of mechanical dislocations by Friedel [16] and has been used, for example, to discuss domain-wall pinning in permanent magnets [17].

Fig. 2 shows the idea behind the Gaunt–Friedel pinning. Since it is a *strong* pinning mechanism, the magnet volume per jump (Barkhausen volume) is given by the density of pinning centers. In the mechanical analogy, this is Friedel's steady-state criterion [16]. The bulk calculation takes into account that $\Delta x \xi^2 = L^3$, which links the unknown domain-wall curvature (or Δx) to the defect density $1/L^3$. The calculation shows that the coercivity is *quadratic* in the pinning strength p, $H_c \sim p^2$. This counterintuitive result reflects the influence of the domain-wall curvature.

In *two dimensions*, the selfconsistent determination of the domain-wall curvature from the average distance between pinning sites involves the volumes $L^2 t$ and $\Delta x \xi t$, and the expression for the pinning field (coercivity) changes to

$$H_c = H_o \sqrt{\frac{p}{6t\gamma}} \qquad (2)$$

where $\gamma \approx 4(AK_1)^{1/2}$ is the domain-wall energy of the continuous film. Since $H_o \sim p$, the coercivity scales as $p^{3/2}$, as compared to the p^2 dependence in the bulk. Equation (2) shows that large domain-wall energies reduce the coercivity. This is because the large domain-wall energies reduce the domain-wall curvature. This effect can be compensated by reducing the film thickness, providing an elegant tool to tune the effective interaction between the clusters and the magnetic properties of the CPRM.

III. DOMAIN-WALL CURVATURE, JITTER, AND PINNING FORCE

The cross-track correlation length ξ is obtained from the domain-wall curvature (Fig. 1), whose determination in analogous to the bulk case. For thin films

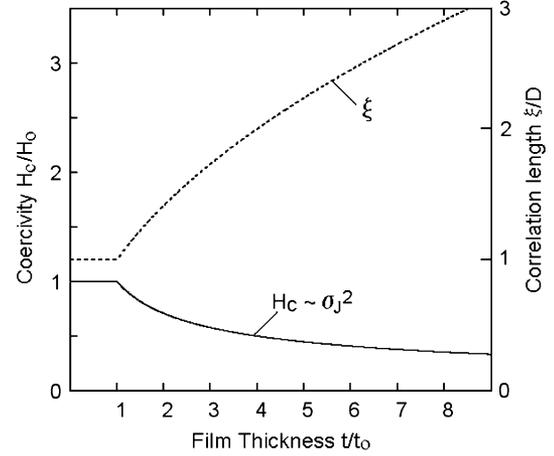$$\xi = L \sqrt{\frac{6t\gamma}{p}}. \qquad (3)$$

Equations (2)–(3) are valid for $p < 6t\gamma$, that is, when the film thickness exceeds some critical value of order $p/6\gamma$. In very thin films, the domain wall are strongly curved and may even wrap around the clusters (Section II-D).

The jitter σ_J, defined as the bit-length fluctuation due to cross-track fluctuations at the bit transition [18], is a simple function of ξ

$$\sigma_J = L^2/(\xi W)^{1/2}. \qquad (4)$$

Here, W is the track width. This means that the jitter *decreases* with increasing cross-track correlation length. Note that (4) differs from the well-known granular-media expression $\sigma_J = L(\xi/W)^{1/2}$, which predicts an increase of the jitter with ξ (grain-size enhancement). In the present system, any increase in ξ is accompanied by a strong reduction of the domain-wall curvature (Fig. 1), and this reduction overcompensates the direct effect of ξ on σ_J. From (3)–(4), we obtain $\sigma_J \sim (H_c)^{1/2}$. Fig. 3 shows the correlation length and the coercivity as a function of the film thickness.

The *pinning force* p entering the above equations has the dimension of a mechanical force. It depends on the particle diameter D, particle height h, film thickness t, and domain-wall energy γ but does *not* depend on the density $(1/L^2)$ of the pinning sites. In practice, the pinning force is therefore be controlled by the dimensions and magnetic properties of the pinning particles. Fig. 4 shows several basic scenarios. In (a), the domain wall goes through the pinning particle and $p \approx \gamma h$. However, the wall in the particle costs domain wall energy, and for thin films the wall may wrap around the particle (b) and $p \approx \gamma t$. In (c), the wall is located below the particle and, aside from magnetostatic corrections, $p \approx \gamma D$. This scenario occur for tall particles (large h/D) deposited onto relatively thick films. For any parameter combination, the physically realized mechanism is determined by the lowest pinning field. When the domain-wall energy is different for particles and continuous thin film, then the basic picture survives but the transitions between Fig. 4(a)–(c) shift.
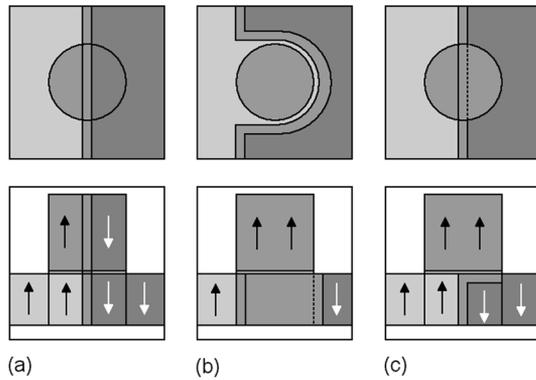
Fig. 4. Pinning strength for different regimes: (a) domain wall in particle, (b) wrapped domain wall, and (c) domain wall under particle.

IV. DISCUSSION AND CONCLUSION

In the proposed cluster-pinned recording media (CPRM), the continuous layer is a thin film with perpendicular anisotropy, few defects and low coercivity. Experimental realizations may be based on high-anisotropy $L1_0$ FePt nanocomposite films, similar to those reviewed by Sellmyer *et al.* [19]. Depending on film thickness and exchange, the magnetization in the clusters switches or remains unaffected during domain-wall motion, as illustrated in Fig. 4. While not achieving the aerial density of single-grain-per-bit media, the media may be useful in the near-to-medium-future. Key advantages are the perpendicular magnetization orientation in the continuous film and the transparent control of interactions, coercivity, and jitter. It may not even be necessary to align the particles, and they can be located *below* the continuous layers, which is tribologically favorable.

With respect to thermal activation, pinning-controlled media are quite robust. This refers to both the activation energy $E_a \sim pD$ associated with the pinning sites and the energy of domain-wall fluctuations. The latter scales as $\gamma t L^4 / \xi^3$ and becomes problematic for very low coercivities.

For both Kersten and Gaunt–Friedel pinning, the pinning force is independent of the domain wall curvature, which is a good approximation for weakly curved walls. Numerical calculations [2], [20] keep track of these corrections but do not consider the large scaling effects (1)–(3).

In conclusion, we propose a new class of nanostructured magnetic materials, consisting of a magnetic particles on a continuous hard layer with perpendicular anisotropy. The clusters act as pinning sites, and the coercivity is controlled by variations in the size, density and coupling of the clusters, as well as film thickness. Unlike soft-magnetic thin films, the structures exhibit very narrow domain walls and are, therefore, able to support high storage densities.

Extending the Gaunt–Friedel pinning mechanism to thin films, we find that the dependence of coercivity on the pinning force obeys a power law with an exponent 3/2, as contrasted to the quadratic dependence in bulk magnets and to the linear dependence for Kersten pinning. Similar scaling laws exist for cross-track correlation length and jitter. The diminished domain-wall curvature due to cluster pinning reduces the jitter, defined as the bit-length fluctuation due to cross-track fluctuations at the bit transition.

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