Efficiently reducing transition curvature in heat-assisted magnetic recording with state-of-the-art write heads

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The curvature of bit transitions on granular media is a serious problem for the read-back process. We address this fundamental issue and propose a possibility to efficiently reduce transition curvatures with state-of-the-art heat-assisted magnetic recording (HAMR) heads. We compare footprints of conventional with those of the proposed head design on different media, consisting of exchange coupled and single phase grains. Additionally, we investigate the impact of various recording parameters, like the full width at half maximum (FWHM) of the applied heat pulse and the coercivity gradient near the write temperature of the recording grains. The footprints are calculated with a coarse grained model, based on the Landau-Lifshitz-Bloch (LLB) equation. The presented simulations show a transition curvature reduction of up to 40%, in the case of a medium with exchange coupled grains and a heat pulse with a FWHM of 40 nm. We further give the reason for the straightening of the bit transitions, by means of basic considerations with regard to the effective recording time window (ERTW) of the write process. Besides the transition curvature reduction the proposed head design yields an improvement of the transition jitter in both down-track and off-track direction.

FIG. 1. (color online) a) Schematic structure of a magnetoresistive HAMR head. b) Temporal evolution of temperature and magnetic field strength for a recording grain during HAMR. The situation, in which pole 1 is used as field source and the proposed situation with pole 2 as field source is compared.

In recent years, heat-assisted magnetic recording (HAMR) is about to become the future high density recording technology for which areal densities well beyond 1 Tb/in$^2$ are achievable. Without heat-assist there does not exist any known possibility to straighten the curvature of written bit transition. Unfortunately, a pronounced curvature significantly deteriorates the signal-to-noise ratio of the recorded track. For HAMR very recently a way was proposed to correct the curvature by means of a magnetic field, which increases from the track center to its edges. However, it is still an open question how to produce such a field shape on the length scale of several tens of nanometers. At least the development of a complex head design will be required.

In this work, we propose a method to correct transition curvatures in HAMR, without the need to change the state-of-the-art head design. The basic idea is to simply reverse the inductive write element or switch the roles of its pole tips. Figure 1(a) schematically illustrates the structure of a magnetoresistive HAMR head, consisting of a GMR read sensor and an inductive write element with an additional laser, which provides the heat-assist. In conventional HAMR the granular medium is moved to the right (as indicated by the arrow). The temporal evolution of temperature and magnetic field at a recording grain is displayed in Fig. 1(b). The grain gets first heated by the laser spot (dashed red curve) before the magnetic field (solid blue curve), produced by pole 1, reaches its maximum value. During cooling of the grain, which is the most important part in the write process, the field can be described in a good approximation as spatially homogeneous. If pole 2 is used as field source the situation changes. First, the field is applied and at its maximum magnitude the grain gets heated (solid red curve). Hence, during cooling of the grain the field already decreases. This allows to significantly reduce the transition curvature as we will show in the following. Note that the marked gap $h_{\text{shift}}$ between the peak of the heat pulse and the start of the field decrease will turn out to be an important design parameter.

In our HAMR model we assume a continuous Gaussian shaped heat pulse with a write temperature of 720 K, which moves with a velocity of $v = 10$ m/s over a granular medium. Depending on the off-track position each grain is subject to a heat pulse with different peak temperatures. Additionally, we assume that the pole tip produces an external magnetic field with a spatially trapezoidal shape in down-track direction, which encloses an angle of $6^\circ$ with the surface normal of the medium. The field gradient is 40 mT/nm (or 400 mT/ns in time) and the write frequency is 1 GHz.
This results in a magnetic write pulse of 1 ns. If not otherwise specified a field strength of 0.8 T and a full width at half maximum (FWHM) of the heat pulse of 40 nm and $h_{\text{shift}} = 5 \text{ nm}$ are assumed.

Figure 2 compares calculated footprints of the write head for a) the conventional case, in which pole 1 (see Fig. 1a) produces the field and b) the proposed case with pole 2 serving as field source. The underlying medium is 10 nm thick and consists of exchange coupled grains (d = 5 nm) with the material parameters EC1 in Table I. The HAMR head tries to reverse the magnetization of the grains from an initial down direction to the up direction. Figure 2 shows the probability of switching $P$ of a grain as function of its down- and off-track position, after 128 write trials. Hence, it can be interpreted as the average footprint in a granular medium.

The simulated footprint of the proposed head with reversed pole tips in Fig. 2 shows a significant reduction of the transition curvature. At the track center the footprint is shifted by almost $-10 \text{ nm}$ along the down-track direction, whereas at the track edge the bit transition almost remains at the same down-track position compared to the conventional head design of Fig. 2b. To quantify the curvature reduction we fit both trailing and leading edge of the footprints (line with a switching probability of 50%) with a quadratic polynomial $cz^2 + bz + a$ [22]. The second order coefficient $c$ is taken as measure for the curvature, yielding a large curvature reduction of almost 40% for both edges of the footprint (see marked row in Table II).

![Image of footprints showing curvature reduction](image)

**TABLE I.** Material parameters of two different exchange coupled grains EC1 and EC2 and a single phase grain SP. $K_1$ is the anisotropy constant, $M_s$ the saturation magnetization, and $T_C$ the Curie temperature of the used materials. $dH_c/dT|_{T \leq T_{i,\text{min}}}$ denotes the average gradient of the coercive field for temperatures below $T_i$, at which $H_c$ becomes smaller than $H_{\text{ext}}$.

|                | EC1 | EC2 | SP |
|----------------|-----|-----|----|
| $K_{1,\text{hard}} [\text{MJ/m}^3]$ | 6.6 | 6.6 | 6.6 |
| $\mu_0 M_{s,\text{hard}} [\text{T}]$ | 1.43 | 1.43 | 1.43 |
| $T_{C,\text{hard}} [\text{K}]$ | 644 | 537 | 537 |
| $K_{1,\text{soft}} [\text{J/m}^3]$ | 0.0 | 0.0 | -   |
| $\mu_0 M_{s,\text{soft}} [\text{T}]$ | 2.16 | 2.16 | -   |
| $T_{C,\text{soft}} [\text{K}]$ | 954 | 795 | -   |
| $dH_c/dT|_{T \leq T_{i,\text{min}}}$ $[\text{mT/K}]$ | 4.8 | 5.6 | 24.2 |

**TABLE II.** Transition curvature reduction for the proposed head design with reversed pole tips compared to a conventional HAMR head. Various grains (see Table I) and design parameters are investigated. $\sigma_{\text{down}}$ and $\sigma_{\text{off}}$ denote the change in the transition jitter in down- and off-track direction, respectively.

$$\text{ERTW}_\uparrow = |t(T_C), t(T_i)| \cap [t_{\text{start}}, t_{\text{final}}].$$ (1)

In HAMR recording grains get heated during the write process to reduce their coercive field. Above the freezing temperature $T_i$ the coercivity decreases below a given write field strength. Hence, there only exists a small temperature range within which the magnetization of a grain can be reversed (between $T_C$ and $T_i$). The first term in Eq. (1) denotes precisely this time win-
Based on this result we investigate the marked points in Fig. 2 in more detail. Figure 3 displays the temporal evolution of the heat pulse and the external field in the marked points of Fig. 2. The time span between $T_C$ and $T_f$ is shown with a gray solid area and ERTW$_f$ corresponding to Eq. 3 is marked with a green striped area.

The ERTW for writing in up direction is then defined as intersection of the latter and the time period of the write pulse in up direction. The findings of Ref. 23 show that ERTW$_f$ must be larger than a threshold value to obtain a switching probability of 100%.

In the case of exchange coupled grains EC2 with lower Curie temperatures in both the soft and the hard magnetic part, the curvature reductions are very similar to those of EC1 grains. Obviously, the Curie temperature does not influence the mechanism, if the gradients of the coercive field $dH_c/dT$ around the freezing temperature are similar. To check how the transition curvature reduction changes if grains with a larger
In summary, we demonstrated an efficient way to reduce the curvature of bit transitions on granular media with state-of-the-art HAMR heads. The idea relies on the reversal of the inductive write element. As a consequence this design produces a decaying magnetic field strength during the effective recording time window ERTW between $T_C$ and the freezing temperature $T_f$ at which the coercive field equals the given magnetic write field. The field gradient shifts bit transitions at the center of the track, but not at the edge of the track, which straightens the transition. This works best for large heat spots, because the decaying magnetic field confines the bit. For exchange coupled grains with a moderate gradient of the coercivity near $T_f$ and a FWHM of 40 nm of the heat pulse, we obtained a curvature reduction of about 40%. The effect lessens for decreasing FWHM and increasing coercivity gradient. Hence, it is less important for ultrahigh density devices with areal densities $>5$ Tb/in², in which the transition curvature will naturally decrease due to the need of materials with a high coercivity gradient and heat spots with a low FWHM. However, the proposed head design can significantly increase the signal-to-noise ratio of current HAMR devices, suffering from the curvature of bit transitions. As a side effect the proposed head design has a positive impact on the transition jitter in both down-track and off-track direction.

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