Write head design for effective curvature reduction in heat-assisted magnetic recording by topology optimization

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The reduction of the transition curvature of written bits in heat-assisted magnetic recording (HAMR) is expected to play an important role for the future areal density increase of hard disk drives. Recently a write head design with flipped write and return poles was proposed. In this design a large spatial field gradient of the write head was the key to significantly reduce the transition curvature. In this work we optimized the write pole of a heat-assisted magnetic recording head in order to produce large field gradients as well as large fields in the region of the heat pulse. This is done by topology optimization. The simulations are performed with dolfin-adjoint. For the maximum field gradients of 8.1 mT/nm, 8.6 mT/nm and 11.8 mT/nm, locally resolved footprints of an FePt like hard magnetic recording medium are computed with a coarse-grained Landau-Lifshitz-Bloch (LLB) model and the resulting transition curvature is analysed. Additional simulations with a bilayer structure with 50% hard and 50% soft magnetic material are computed. The results show that for both recording media, the optimized head design does not lead to any significant improvement of the written track. Thus, we analyse the transition curvature for the optimized write heads theoretically with an effective recording time window (ERTW) model. Moreover, we check how higher field gradients influence the curvature reduction. The results show that a simple optimization of the conventional head design design is not sufficient for effective curvature reduction. Instead, new head concepts will be needed to reduce transition curvature.

I. INTRODUCTION

In heat-assisted magnetic recording (HAMR)1–3 a heat pulse is included to the writing process to overcome the so-called recording trilemma4 and make high-anisotropy grains writable with the available head fields. However, in granular media, the curved thermal profile of the heat pulse in combination with a spatially relatively homogeneous head field gives rise to a significant curvature at transitions between bits.5–7 This transition curvature is expected to be a serious problem for the read-back process in HAMR since the signal-to-noise ratio (SNR) is reduced.8 Different methods to efficiently reduce transition curvature in HAMR have been proposed, for example a write head field design by Zhu et al.8,9 The present work is based on the publication by Vogler et al.10 where a recording head design with flipped write and return pole to efficiently reduce transition curvature is suggested. For the flipped head design writing of the bit happens between the near field transducer (NFT) and the return pole, whereas for the conventional design writing happens near the write pole. The position where the bit is written for the different design is indicated by the grey arrows in Figure 1(a) and (b). The different writing position leads to a different behavior of the write field during the cooling process of the heat pulse. For the conventional design, the applied field is spatially relatively homogeneous during the cooling process (see Figure 1(c)). In contrast to this, shown in Figure 1(d), the field decreases during cooling for the flipped design which leads to a field gradient in down-track direction. This field gradient turned out to be the key for the curvature reduction. For this reason, the head field gradient in down-track direction is an important parameter in the simulations.

In this work, we compute the realistic field gradient for a flipped design, that follows the model of a state-of-the-art recording head design10 at the position where the heat pulse is cooling down. To optimize the head, we design a write pole that maximizes both the field and the field gradient at the required position. This is done by topology optimization14 an application of the inverse magnetostatic problem15. With the resulting fields and field gradients we compute locally resolved switching probability phase diagrams with a coarse-grained LLB model16 for both pure hard magnetic recording material and an exchange spring structure with 50% hard and 50% soft magnetic material. From this locally resolved phase diagrams, we can then analyse the transition curvature. Additionally, we interpret the results in the context of the effective recording time window (ERTW) model by Vogler et al.11,16. This paper is structured as follows: In Section II, a theoretical framework of the simulation methods is presented and the simulation and material parameters are given. The results are presented in Section III and discussed in Section IV.

II. THEORETICAL FRAMEWORK

A. Topology optimization

To solve the topology-optimization problem, the density method, which is also known as solid isotropic microstructure with penalization (SIMP), is used.17,18
First, the geometry is meshed with a tetrahedral mesh. At each element of the mesh the density \( \rho \) of the material is considered and a value between 0 (void) and 1 (material) is assigned to it. This leads to a penalization parameter \( k \) to penalize those densities that are intermediate. The materials in the simulations are approximately described by linear material laws. For the soft magnetic material, the material law reads as

\[
B_s = \mu_0 (H_s + M_s) = \mu_0 \mu_r H_s
\]

where \( \mu_r \) is the relative permeability. \( \mu_0 \) denotes the vacuum permeability. For the hard magnetic material, there holds

\[
B_p = \mu_0 \mu_m H_p + \mu_0 M_0
\]

with the recoil permeability \( \mu_m \). For a permanent magnetic region \( \Omega_s \subset \mathbb{R}^3 \), the magnetization as a function of the density \( \rho \) can be written as

\[
M(\rho) = \rho^k M_0
\]

with the density value \( \rho \in [0, 1] \) of one element and the penalization parameter \( k \). For hard magnetic materials, \( k = 1 \) is a good choice. For a soft magnetic design region \( \Omega_s \subset \mathbb{R}^3 \), the magnetic susceptibility \( \chi \) can be reformulated as a function of the density to

\[
\chi(\rho) = \chi_0 \cdot \rho^k
\]

and thus for the relative permeability, there holds

\[
\mu_r(\rho) = (\mu_{r0} - 1) \rho^k + 1.
\]

In this way it can be used for topology optimization. In the case of soft magnetic material, \( k = 4 \) leads to good results. The topology-optimization problem that needs to be solved is given by

\[
\text{Find : } \min_{\rho} J(\rho)
\]

subject to:

\[
\int_{\Omega_i} \rho(r) dr \leq V; \quad 0 \leq \rho(r) \leq 1, r \in \Omega_i
\]

where \( J \) is the objective function, \( V \) is the maximum volume of the design as a constraint and \( i \in \{s,p\} \) defines the soft and permanent magnetic region, respectively. The objective function used to maximize the magnetic field and the \( z \)-field gradient is given by minimizing

\[
J(\rho) = \int_{\Omega_{\text{field}}} \frac{1}{|\nabla H_z(\rho)|^2} dr + \int_{\Omega_{\text{field}}} \frac{1}{|H_z(\rho)|^2} dr + \lambda \int_{\Omega_{\text{opt}}} \rho(1 - \rho) dr,
\]

where \( \Omega_{\text{opt}} \) is the region of the material that is optimized, \( H_z(\rho) \) is the \( z \)-field and \( \nabla H_z(\rho) \) is the gradient of the \( z \)-field. \( \lambda \) is a penalization parameter. The topology-optimization problem is solved by a finite element method (FEM) which is based on the open-source library FEniCS for solving partial differential equations (PDEs) and the library dolfin-adjoint. Dolfin-adjoint automatically determines and solves adjoint linear equations using PDEs which are discretized with finite elements. The minimization problem is solved using the L-BFGS-B method, a limited-memory quasi-Newton solver for bound-constrained optimization.

**B. Head design parameters**

In the topology-optimization simulations, a write head is optimized, which consists of a write and a return pole, a permanent magnet to simulate the core magnetized by a coil and a 50 nm thick soft magnetic underlayer (SUL). Additionally, in some simulations a backshield is considered. All components and the dimensions of the write head are marked in Figure 2 and summarized in Table 1. The tip of the write pole and the backshield, if considered, are the parts of the write head that are optimized by topology optimization. Except the permanent magnet, all other parts of the write head consist of soft magnetic material.

The material of the recording head is assumed to be FeCo. Hence, a relative permeability \( \mu_r = 18000 \) and a saturation polarization of 2.4 T are assumed. It is
considered that the coil magnetizes the core with 0.8 T in \( x \)-direction which is modeled by the means of a permanent magnet that is magnetized in \( x \)-direction with 0.8 T. This field is chosen because then the maximum magnetization of the initial design is slightly below the saturation polarization of the material.

The field and the field gradient are computed and optimized at the position where the recording medium hit by the heat spot produced by the NFT is already cooling down. This position is assumed to be 50 nm away from the pole tip in \( x \)-direction.

Since small head to media spacings (HMS) are needed, to get high areal storage density, the HMS is assumed to be 5 nm.

Four different starting geometries are considered. The starting geometries are basic geometries of dimensions \( x_{\text{write}} \times y_{\text{total}} \times z_{\text{opt}} \), where the density initially is 1 for each element. During the optimization process, the density of each element is adjusted. The difference between the geometries is the dimension in \( x \)-direction and the fact if a backshield is considered or not. The dimensions in \( y \)- and \( z \)-direction are the same for all starting geometries and equal to \( y_{\text{total}} \) and \( z_{\text{opt}} \), respectively. The first geometry to be optimized, is one with dimension \( x_{\text{write}} = 100 \) nm and no backshield. This one is referred to as Basic\(_{100}\). The second geometry also has dimension \( x_{\text{write}} = 100 \) nm. However, for this geometry a backshield with \( x_{\text{back}} = 100 \) nm is additionally considered and optimized. Afterwards, this geometry is called Backshield\(_{100}\). The last geometries are similar to the former ones but with dimensions \( x_{\text{write}} = 200 \) nm and \( x_{\text{back}} = 200 \) nm. They are labeled Basic\(_{200}\) and Backshield\(_{200}\). The \( x_{\text{write}} \) and \( x_{\text{back}} \) values of the different geometries are summarized in Table II.

After the optimal head designs are determined via topology-optimization, additional simulations with magnum.fe\(_{32}\) that include a coil instead of a permanent magnet are performed. These coil-simulations are performed in order to determine realistic fields with the optimized head designs. Here, all parts of the write head are considered to be soft magnetic with the above material parameters. The current density inside the coil is assumed to be \( 2.5 \times 10^{10} \) A/m\(^2\), which is below the current density limit of \( 10^{12} \) A/m\(^2\).

### III. RESULTS

#### A. Field gradients

Forward simulations show that the field gradient of the initial flipped design, which follows a state-of-the-art head design\(_{12,13}\) at 50 nm distance from the write pole is approximately 2.2 mT/nm. In Figure 3 the resulting fields from the coil simulations with the optimized geometries are plotted. The results show that the best outcome can be achieved for a geometry with a pole tip with \( x_{\text{write}} = 200 \) nm and an additional backshield with \( x_{\text{back}} = 200 \) nm. Here, the maximum field gradient is 11.8 mT/nm. The optimized Backshield\(_{200}\) geometry is shown in Figure 4. Note that all optimized geometries are similar and show a tapered shape. Recapitulating, the resulting write fields and field gradients for the different geometries are summarized in Table II.

#### B. Curvature reduction

To analyse the curvature reduction, switching probability phase diagrams are computed with the help of a coarse-grained model based on the stochastic Landau-Lifshitz-Bloch equation (LLB)\(_{16}\) for a FePt like granular recording medium. The material parameters of the medium can be seen in Table III. In the simulations a continuous laser pulse with Gaussian shape and a full width at half maximum (FWHM) of 60 nm is considered. The temperature profile of the heat pulse is given by

\[
T(x, y, t) = (T_{\text{write}} - T_{\text{min}})e^{-\frac{(x-vt)^2+y^2}{2\sigma^2}} + T_{\text{min}} \\
= T_{\text{peak}}(y) \cdot e^{-\frac{(x-vt)^2}{2\sigma^2}} + T_{\text{min}}
\]

with
| xSUL | ytotal | ztotal | xoff | yoff | zoff | xwrite | xreturn | distw | distb | xfield | yfield |
|------|--------|--------|------|------|------|--------|---------|-------|-------|--------|-------|
| 2 µm | 5 µm   | 13 µm  | 1 µm | 3 µm | 3 µm | 2 µm   | varied  | 200 nm| 1 µm  | varied  | 50 nm | 100 nm | 100 nm |

TABLE I. Approximated dimensions of an initial flipped recording head design as marked in Figure 2.

| Geometrie                        | xwrite [nm] | xback [nm] | µ₀H [T] | Max. µ₀dH/dx [mT/nm] |
|----------------------------------|-------------|------------|---------|----------------------|
| Conventional                     | 100         | ---        | 0.8     | ---                  |
| Initial flipped design           | 100         | ---        | 0.2     | 2.2                  |
| Basic100                         | 100         | ---        | 0.4     | 4.1                  |
| Basic200                         | 200         | ---        | 0.7     | 8.6                  |
| Backshield100                    | 100         | 100        | 0.67    | 8.1                  |
| Backshield200                    | 200         | 200        | 0.8     | 11.8                 |

TABLE II. Resulting fields and field gradients produced by the write heads which are optimized with the help of topology optimization for a FeCo like head material. The field and its gradient of a conventional head are added for comparison.

![Graph](image)

FIG. 3. Comparison of the fields of the topology optimized geometries for a FeCo like head material. The magnetic field is plotted over the x-length of the 100 nm x 100 nm wide fieldbox (marked red in Figure 2). At x = 0, the fieldbox is 50 nm away from the edge of the write pole.

![Image](image)

FIG. 4. Comparison of the initial flipped head design (grey) and the topology optimized write pole (red) with a backshield (blue) with xwrite = 200 nm and xback = 200 nm (red). (a) Front view and (b) rear view with backshield of the optimized write pole.

\[ \sigma = \frac{\text{FWHM}}{\sqrt{8 \ln(2)}} \]  

The speed \( v \) of the write head is assumed to be 15 m/s. \( x \) and \( y \) are the down-track and the off-track position of the grain, respectively. In the simulations both the down-track position \( x \) and the off-track position \( y \) are variable. The initial and final temperature of all simulations is \( T_{\text{min}} = 300 \) K. The write temperature \( T_{\text{write}} \) is chosen to be 800 K. The applied field is modeled as a trapezoidal field with a field duration of 0.57 ns and a field rise and fall time of 0.1 ns. The angle of the applied field with respect to the normal is assumed to be 22 deg. In each phase point 128 HAMR simulation simulations of a recording grain are performed.

In the phase diagrams the switching probability of a recording grain is shown as a function of the down-track position \( x \) and the off-track position \( y \). First, the phase diagram is computed for a spatially homogeneous field which approximates a conventional recording head design. Additionally, footprints for optimized geometries with field gradients of 8.6 mT/nm (Basic200), 8.1 mT/nm (Backshield100) and 11.8 mT/nm (Backshield200) are computed. The geometries with field gradients 2.2 mT/nm (Initial flipped) and 4.1 mT/nm (Basic100) are not further considered since the phase diagrams show too much noise to get reliable results. Note, that different write fields (see Table II) are used for the simulations with different field gradients as seen in Table II. In Figure 5 the resulting switching probability phase diagrams can be seen. There are some visible differences between the footprints of the different field gradients.

One can see that for the flipped designs the recording performance is worse than for the conventional design.
where a homogeneous field is assumed. This can be seen by the increase of jitter in down-track direction and the reduction of the maximum switching probability \( P_{\text{max}} \). \( P_{\text{max}} \) and the jitter can be determined by fitting the \( P(x) \)-curve at one temperature with a Gaussian cumulative distribution function

\[
\Phi_{\mu,\sigma^2} = \frac{1}{2} (1 + \text{erf}(\frac{x - \mu}{\sqrt{2\sigma^2}})) \cdot p
\]

with

\[
\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\tau^2} d\tau,
\]

where the fitting parameters are the mean value \( \mu \), the standard deviation \( \sigma \) and the mean maximum switching probability \( p \in [0,1] \). The standard deviation \( \sigma \) determines the steepness of the transition function and is a measure for the transition jitter. The temperature at which the down-track jitter is determined is \( T_{\text{peak}} = 760 \text{ K} \). The resulting jitter and \( P_{\text{max}} \) values are summarized in Table IV. Additionally, it can be seen that the grains are written at larger off-track positions for increasing field gradients and the resulting lower write fields. The various write fields lead to writing of the grains at different peak temperatures. For smaller write fields the grains are written at higher temperatures only whereas they are written at lower temperatures for higher fields. The convention

\[
T_{\text{peak}}(y) = (T_{\text{write}} - T_{\text{min}}) e^{-\frac{y^2}{2\sigma^2}} + T_{\text{min}}.
\]

shows that with higher write fields, the off-track edge of a bit shifts to larger off-track positions, because the minimum temperature necessary to write a grain is smaller.

For a detailed analysis of the transition curvature, the full down-track range \( \Delta x \) in which the bit is written with \( P_{\text{max}} \geq 50\% \) is computed. \( \Delta x \) is marked in Figure 5 as the distance between the black dashed lines. Because of the different off-track widths \( \Delta y \) in the phase diagrams for the different geometries, it is necessary to scale the curvature parameter with \( \Delta y \). This is done, since the track width is usually kept constant in magnetic recording. In reality the track-width can for example be steered by controlling the peak temperature \( T_{\text{peak}} \) or the full width at half maximum\([11]\). With the curvature parameter \( c = \Delta x/\Delta y \), the curvature can be reliably analyzed. Note that \( c \) is equivalent to the curvature parameter used by Vogler et al\([11]\) when multiplied by \( \Delta y \) for scaling reasons. There holds

\[
c = \frac{\Delta x}{\Delta y} \equiv cp \cdot \Delta y
\]

where \( cp \) is the curvature parameter defined by Vogler et al\([11]\). The curvature analysis shows that the curvature reduction for the Backshield\(200\) flipped head design with a field gradient of 11.8 mT/nm (Backshield\(200\)) is increased for both the Basic\(200\) and the Backshield\(100\) design compared to the conventional design. The curvature reduction for the Backshield\(200\) flipped head design with a field gradient of 11.8 mT/nm is about 1.3\%. Detailed information about the curvature parameters can be seen in Table IV.

C. Exchange Spring Recording Medium

Since the curvature reduction is negligible for pure hard magnetic recording media in combination with the flipped head design, a bilayer structure with 50\% hard and 50\% soft magnetic material is tested as recording material. In the original paper by Vogler et al\([11]\), a bi-layer structure showed significantly higher curvature reduction than the pure hard magnetic recording medium. The total height of the grains is again \( h = 8 \text{ nm} \). The material parameters of the soft magnetic composition can be seen in Table IV. Phase diagrams for the different head designs are calculated and the off-track width is again normalized for comparability reasons. They are shown in Figure 5. Again, the jitter \( \sigma_{\text{down}} \) and \( P_{\text{max}} \) are calculated for the footprints and compared in Table IV. Due to the higher Curie temperature of the exchange spring recording medium, the down-track jitter is determined at 800 K. For the exchange spring recording material the behavior of the curvature is similar to that for pure hard magnetic recording media and seems to be even worse. For the Backshield\(200\) head design the decrease of the curvature is only 0.08\% compared to the conventional de-
TABLE III. Material parameters of a FePt like hard magnetic granular recording medium. Note, that different material parameters for the recording medium were used compared to the original work of Vogler et al.\textsuperscript{13}

| Geometry          | c (%) | \( P_{\text{max}} \) (%) | \( \sigma_{\text{down}} \) (%) |
|-------------------|-------|--------------------------|-------------------------------|
| Basic\textsubscript{200} | +1.4  | -5.5                     | +118.7                        |
| Backshield\textsubscript{100} | +3.8  | -7                       | +113.5                        |
| Backshield\textsubscript{200} | -1.35 | -2.3                     | +28.4                         |

TABLE IV. Resulting transition curvature, \( P_{\text{max}} \) and jitter parameters of the different flipped head designs in combination with a pure hard magnetic recording material compared to a conventional recording head design.

The first term on the right hand side gives the time window in which the grains can be written in HAMR, namely in the temperature range between the Curie temperature \( T_c \) and the freezing temperature \( T_{\text{freeze}} \). At the freezing temperature the coercivity decreases below the given field strength such that the grain cannot be written any longer. To calculate the ERTW, the freezing temperature has to be estimated. For this reason, hysteresis loops are simulated for various temperatures with VAMPIRE\textsuperscript{35}. At each fixed temperature, 128 hysteresis loops are computed and the temperature dependence of the coercive field \( dH_c/dT \) is determined. If the coercive field at a fixed temperature is lower than the write field, the temperature is a possible write temperature. Since the magnitude of the write field is not constant for the flipped head designs, a correction factor is included in the model. With the correction factor the magnitude of the field is updated according to the field gradient and the resulting write field is used for the determination of the freezing temperature.

The second term gives the time window in which the field points in the desired write direction, which in the following is regarded as pointing upwards without loss of generality. With this ERTW definition a switching probability phase diagram without noise can be computed for different materials and various fields and field gradients. The switching probability of a recording grain can be computed via\textsuperscript{35}

\[
p = \min \left( \frac{\text{ERTW}_\uparrow}{\Theta_{\text{ERTW}}}, 1 \right) \left[ 1 - \min \left( \frac{\text{ERTW}_\downarrow}{\Theta_{\text{ERTW}}}, 1 \right) \right]. \tag{16}
\]

The first term gives the probability that a bit is written in write direction. Since the probability cannot exceed 1, the minimum between 1 and \( \Theta_{\text{ERTW}} \) is taken. \( \Theta_{\text{ERTW}} \) is a threshold of the ERTW that gives the time that must be exceeded for successful switching to occur. It can be determined as a fit parameter to reproduce the results by the LLB model. The second term is the probability that a grain is overwritten after it was already aligned in write direction. Together, \( p \) describes the joint probability to switch a bit in write direction and not reverting it afterwards. From the phase diagrams, the transition curvature is calculated and it is determined how much the theoretical curvature reduction should be.

For the Backshield\textsubscript{200} geometry, the theoretically expected curvature reduction is about 1% for the pure

\[ \text{ERTW}_\uparrow = \left[ t(T_c), t(T_{\text{freeze}}) \right] \cap \left[ t_{\text{start}, \uparrow}, t_{\text{final}, \uparrow} \right] \tag{15} \]
TABLE V. Material parameters of the soft magnetic composition of the bilayer structure.

| Geometry     | $c$ (%) | $P_{\text{max}}$ (%) | $\sigma_{\text{down}}$ (%) |
|--------------|---------|-----------------------|----------------------------|
| Basic200     | +1.38   | -2.5                  | -16.2                      |
| Backshield100| +1.9    | -1.19                 | -4.7                       |
| Backshield200| -0.08   | +/ -0.0               | -19                        |

TABLE VI. Resulting transition curvature, $P_{\text{max}}$ and jitter parameters of the different flipped head designs in combination with an exchange spring recording medium compared to a conventional recording head design with the same recording material.

| Geometry     | $T_C$ (K) | Anisotropy const. $K_1$ (MJ/m$^3$) | $J_s$ (T)   |
|--------------|-----------|-----------------------------------|-------------|
|              | 740.9     | 0                                 | 1.35        |

hard magnetic recording material compared to the conventional design. This agrees very well with the curvature reduction resulting from the LLB simulations. For the exchange spring bilayer structure, the ERTW model predicts a curvature reduction of about 1.7%. The very small value achieved by the LLB simulation (−0.08%) results from the switch of the transition around zero. This switch does not happen in the analytical ERTW model and comes from the stochastic nature of the LLB model. Additionally, with the ERTW model, it can be analyzed with reasonable computational effort how the transition curvature reduction depends on the field gradient. The resulting curvature reduction values can be seen in Table VII. They display that the curvature reduces linearly with the field gradient. Moreover, a higher potential for the curvature reduction can be seen for the exchange spring bilayer structure. However, even with field gradients up to 40 mT/nm, the bilayer structure did not show as high curvature reduction as the exchange spring media used by Vogler et al. This can most likely be explained by the different damping constants used in the hard magnetic material. In the work by Vogler et al., the damping constant is $\alpha_{\text{HM}} = 0.1$ whereas it is $\alpha_{\text{HM}} = 0.02$ in this work. This leads to different $dH_c/dT$ gradients and thus to the different curvature behavior. This shows that damping plays a key role for the curvature reduction.

IV. DISCUSSION

To conclude, in this work we tried to optimize the design of the write pole of a recording head for heat-assisted magnetic recording in order to reduce transition curvature. The write pole of the head was optimized in a way to maximize both the $z-$field and the $x-$field gradient at the position where the applied heat pulse is cooling down. This was done with the help of topology optimization which is an application of the inverse magnetostatic problem. Different starting geometries were considered. The comparison of the different geometries to a conventional recording head design showed the best results for a write pole and an additional backshield which both have dimension 200 nm in down-track direction. The resulting field gradient is then 11.8 mT/nm. The optimized geometries are all similar. They all have smooth edges, a tapered shape with a tip in the middle and the peak is skewed in $x-$direction such that the distance of the pole tip to the recording medium is close to the fieldbox and larger on the side away from it (see Figure 1). Since all optimized geometries are similar, the field and the field gradient could be maximized further by optimizing even larger write poles with an additional backshield. Another option to further increase the field gradient produced by the write pole is a design where the NFT is closer to the write pole.

We calculated switching probability phase diagrams of FePt like head magnetic recording media for the different optimized field gradients. It is noteworthy that the switching performance, in terms of down-track jitter and maximum switching probability, for all flipped head designs is worse than that of the conventional head design. Both, the AC and the DC noise increase for the flipped head designs. The performance loss results most likely from the smaller write fields that are produced by the flipped head designs. Analyzing the transition curvature showed that the curvature reduces only marginally even for the Backshield200 design where the highest write field and field gradient can be achieved. An idea how to improve the curvature reduction is to use an exchange spring medium\textsuperscript{[17][18]}\textsuperscript{[19]}\textsuperscript{[20]}. The soft magnetic layer acts as a write assist and thus smaller write fields are required to write the grains. For the conventional design the curvature of the exchange spring recording medium is larger than that of the pure hard magnetic medium. Thus, the curvature reduction potential was expected to be higher for the exchange spring media. We computed switching probability phase diagrams for the different head designs in combination with the exchange spring recording media. Surprisingly, the curvature reduction for the Backshield200 design was even smaller than for the pure hard magnetic material. To understand why the curvature reduces only so little, we analyzed the results in the context of the effective recording time window (ERTW) model that was used in the paper by Vogler et al.\textsuperscript{[11]} The ERTW model confirmed the results of the LLB model. Hence, we can conclude that the marginal reduction of the curvature is not a consequence of noise. The analysis also pointed out that the exchange spring recording medium shows a larger potential for curvature reduction if higher field gradients are used but even here the curvature reduction is only marginally.

In conclusion, we did not see any improvement of the transition curvature for the resulting field gradients of
the optimized flipped head design in combination with pure hard magnetic and exchange spring recording media. The results showed that a simple optimization of the conventional head design is not sufficient for effective curvature reduction but that new head concepts have to be introduced to reduce transition curvature.

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| Field gradient [mT/nm] | c (%) HM | c (%) HM/SM |
|------------------------|----------|-------------|
| 12                     | -1.0     | -1.7        |
| 16                     | -1.6     | -3.64       |
| 20                     | -2.09    | -5.58       |
| 24                     | -2.59    | -7.5        |
| 28                     | -3.38    | -9.48       |
| 32                     | -4.6     | -11.4       |
| 36                     | -5.2     | -13.11      |
| 40                     | -5.8     | -14.2       |

TABLE VII. Curvature reduction in % compared to a conventional design for pure hard magnetic recording material (HM) and an exchange spring bilayer structure (HM/SM) calculated with the ERTW model.

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