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Breaking the thermally induced write error in heat assisted recording by using low and high T_c materials

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Heat assisted recording is believed as a key future recording technology. In the work of H. J. Richter *et al.* [J. Appl. Phys. **111**, 033909 (2012)] it is stated that storage densities will be limited to 15–20 Tbit/in² due to thermally induced write errors. In this letter we propose a composite structure consisting of two materials with different Curie temperatures. In this composite material the thermal write error is negligible up to areal densities of about 50–100 Tbit/in². © 2013 AIP Publishing LLC [http://dx.doi.org/10.1063/1.4802882]

In magnetic recording the areal density is believed to be limited by the recording trilemma.¹ In order to break the recording trilemma various schemes are proposed such as bit patterned media,² inhomogeneous reversal schemes (ECC,³ exchange spring, and graded media⁴), and heat assisted recording.^{5,6} ECC (Exchange Coupled Composite Media) media and exchange spring media are widely discussed in academia and industry in order to gain beneficial effects in heat assisted recording. In Ref. 7 it is shown that ECC media with a soft magnetic layer on top of a hard magnetic layer reduce anisotropy fluctuations in heat assisted recording.

Recently, the recording trilemma was extended to a recording quadrilemma.⁸ Richter *et al.* have shown that thermally induced recording errors occur due to thermodynamical processes during the recording process. These errors are negligible for recording at room temperature. However, for the future recording concept of heat assisted recording these errors are believed to be the limiting factor.⁹

In the work of Richter *et al.* FePt is investigated as heat assisted recording media. The material properties are assumed to scale as function of temperature as follows:⁹

$$J_s(T) = J_s(T_0) \sqrt{\left(1 - (T/T_c)^{2.5}\right)}, \quad (1)$$

$$K_1(T) = K_1(T_0) (J_s(T)/J_s(T_0))^2. \quad (2)$$

Here, $J_s(T)$ and $K_1(T)$ are the magnetic polarization and magnetic anisotropy constant as function of temperature, respectively. T_0 denotes zero temperature. The temperature dependence of these properties is shown in Fig. 1. In order to record the ultra-high coercive material FePt the temperature has to be as high as $T_{wr} = 748$ K during the recording process in order to lower the coercive field to values around 1.0 T. Here we have assumed that the recording head can generate a field of 1.0 T. It is worth mentioning that in Ref. 9 a write temperature of $T_{wr} = 740$ K was assumed. This assumption can be justified by using some kind of write assist or the fact that the switching field is lowered due to thermal fluctuations. As consequence generally larger areal densities are obtained in Ref. 9; however, all conclusions of this paper are independent on these non-significant variations of T_{wr} . The temperature $T_{wr} = 748$ K in this work is just below the Curie

temperature of $T_c = 750$ K. As a consequence of the high temperature, not only the anisotropy decreases but also the saturation polarization $J_s(T_{wr}) = \mu_0 M_s(T_{wr})$ decays significantly (M_s denotes the saturation magnetization). Due to the small saturation polarization at this high temperature thermally induced write errors occur. In the one grain per bit limit the BER (bit error rate) can be expressed as⁸

$$BER = \exp\left(-\frac{2J_s(T_{wr})VH_{wr}}{k_B T_{wr}}\right), \quad (3)$$

where T_{wr} is the temperature during the write process, H_{wr} the maximum write field, k_B the Boltzman constant, and V the particle volume which is equal to the bit. In Ref. 8 it is assumed that the relation of the areal density (AD) and the particle volume V can be approximated as

$$AD = \alpha V^{-2/3}, \quad (4)$$

where α is the areal packing fraction of the storage islands, which is assumed to be $\alpha = 0.5$. Substituting Eq. (4) into Eq. (3), the areal density can be expressed as function of the BER⁸

$$AD = \alpha \left(\frac{2J_s(T_{wr})H_{wr}}{k_B T_{wr} \ln(1/BER)}\right)^{2/3}. \quad (5)$$

The switching field as function of temperature is estimated by the Stoner–Wohlfarth theory using

$$\mu_0 H_s(T) = \mu_0 \frac{2K_1(T)}{J_s(T)}. \quad (6)$$

The temperature dependence of the anisotropy constant $K_1(T)$ and the saturation polarization $J_s(T)$ for FePt is shown in Fig. 1. Fig. 2 shows the switching field according to Eq. (6) as function of temperature. At the temperature of $T_{wr} = 748$ K a write field of $\mu_0 H_s(T) = 1.0$ T is required to reverse the bit. At this temperature the magnetic polarization is $J_s = \mu_0 M_s(T_{wr}) = 0.10$ T. This small saturation polarization leads to the above mentioned thermally induced write errors. The AD as function of BER is shown in Fig. 3 for the FePt media using Eq. (5).

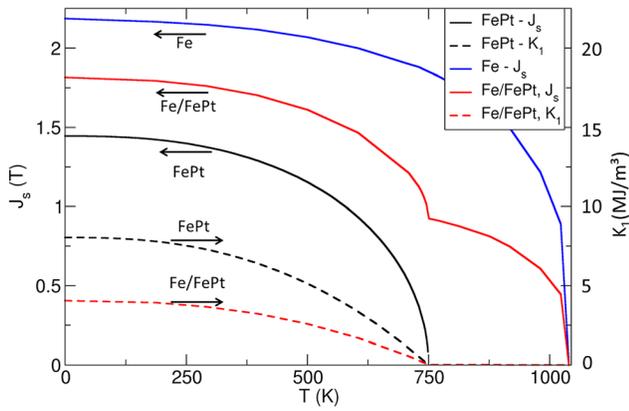


FIG. 1. Temperature dependence of saturation polarization J_s and anisotropy constant K_1 for Fe, FePt, and the averaged composition Fe/FePt consisting of 50% Fe and 50% FePt.

In this letter we present two simple media grain designs which allow overcoming the thermally induced write error. The media design consists of a composition of two materials as shown in Fig. 4. One material has a small Curie temperature and the other material has a large Curie temperature.

As an example we investigate the recently fabricated FePt/Fe exchange spring media.^{10,11} The Curie temperature of Fe is $T_c = 1040$ K (Ref. 12). Due to the fact that the heating of the media is restricted to the surface of the media,¹³ we assume that the material with low T_c material is located next to the pole tip and the softer high T_c material below it. This arrangement of soft/hard layers is opposite to commonly employed exchange spring and ECC media. The temperature dependence of the saturation polarization (Fig. 1) is extracted from Ref. 12. The magnetic anisotropy of Fe can be neglected. In the following we assume the media (Fe/FePt–single domain) having a column length smaller than the exchange length of the hard magnetic material $l = \sqrt{A/K_1}$. As a consequence the reversal process occurs almost coherently in the soft magnetic and hard magnetic region.^{14–16} For this coherent rotation the material parameters, which influence the reversal process, can be averaged over the entire media grain. In the following we assume a

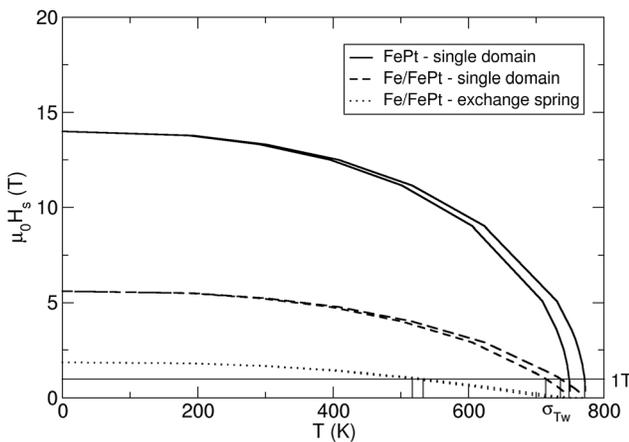


FIG. 2. Switching field of three different media grain composition as function of temperature. The second line for each switching field as function of temperature shows the changed switching field as function of temperature if the Curie temperature is increased by 3%. The resulting σ_T at which the medium switching field is reduced to 1.0T is shown.

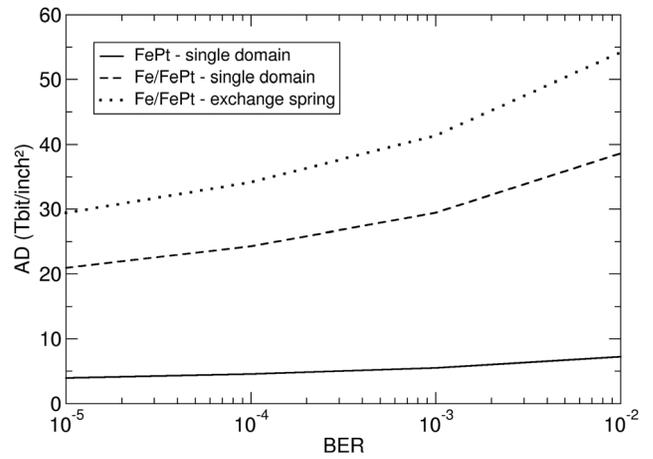


FIG. 3. AD of three different media grain composition as function of BER.

fraction of 50% FePt and 50% Fe, respectively. The average saturation polarization and magnetic anisotropy are shown in Fig. 1. Due to the fact that the Curie temperature of Fe is much larger than that of FePt the average saturation polarization is still large, close to the Curie temperature of FePt. The switching field as function of temperature calculated with Eq. (6) is shown in Fig. 2. The switching field is 1.0 T at a temperature of $T_{wr} = 714$ K. The average saturation polarization at this temperature is as high as $J_r = 1.18$ T. Since the thermally induced write error decays exponentially with the magnetic polarization (Eq. (3)) small write errors occur allowing for low BER. The areal density as function of BER is shown in Fig. 3. For a particle size which corresponds to an $AD = 38$ Tb/in² the $BER = 10^{-2}$.

As a second media design (Fe/FePt–exchange spring) the column length of the recording grain is increased above the exchange length of the hard magnetic material. As a consequence the reversal process occurs via formation of a domain wall. The switching field can be calculated as given by Kronmüller and Goll¹⁷ using

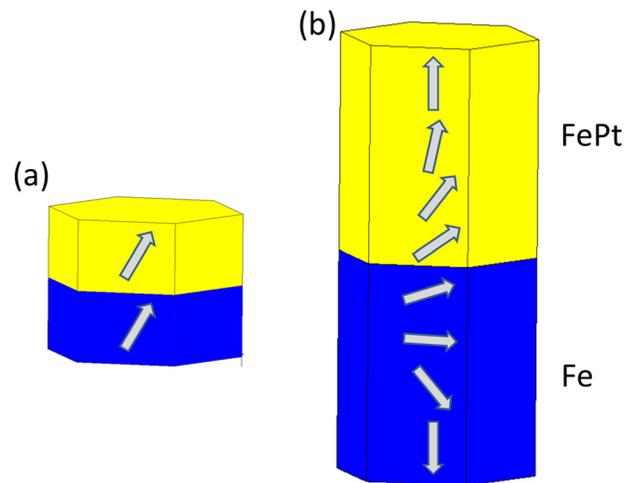


FIG. 4. Two media designs: (a) Fe/FePt–single domain. Hard magnetic FePt layer is deposited on soft magnetic Fe. The column length of the grain is smaller than the exchange length of FePt. The reversal process is quasi homogeneous rotation. (b) Fe/FePt–exchange spring. Column length is larger than the exchange length. The media grain reversed via formation of a domain wall.

$$\mu_0 H_s = \mu_0 \frac{2K_{\text{hard}}}{J_{s,\text{hard}}} \frac{1 - \varepsilon_K \varepsilon_A}{(1 + \sqrt{\varepsilon_J \varepsilon_A})^2}. \quad (7)$$

The ratio of the material parameters of the soft layer to the hard layer are given by the ratio of the anisotropy constants, $\varepsilon_K = K_{\text{soft}}/K_{\text{hard}}$, the ratio of the exchange constants, $\varepsilon_A = A_{\text{soft}}/A_{\text{hard}}$, and the ratio of the magnetic polarizations, $\varepsilon_J = J_{s,\text{soft}}/J_{s,\text{hard}}$. For the temperature dependence of the exchange constant we assume¹⁸

$$A(T) = A(T_0)(M_s(T)/M_s(T_0))^{1.7}. \quad (8)$$

The switching field as function of temperature is shown in Fig. 2. Here, we have used the temperature scaling of the material properties in each material phase according to the equations given above. The switching field is calculated using Eq. (7). The particle is switched already at the relative low temperature of $T_{\text{wr}} = 516$ K. The saturation magnetization at this temperature is as high as $J_r = 1.42$ T. Using Eq. (5) in order to calculate the areal density for a $BER = 10^{-2}$ shows that thermal write are not the limiting factor up to AD of 54 Tbit/in² (see also Table I). If a write field of 1.6 T is assumed thermal write errors do not limit the areal densities up to 110 Tbit/in².

Finally, we investigate the position jitter of the three different media designs. Two contributions of transition jitter are investigated, i.e., (i) jitter due to variation of the anisotropy constant σ_{K1} and (ii) jitter due to variations of the Curie temperature σ_{Tc} .

For the calculation of the jitter contribution (i), the thermal effective head field gradient is evaluated as

$$\mu_0 \frac{\partial H_s}{\partial x} = \mu_0 \frac{\partial H_s}{\partial T} \frac{\partial T}{\partial x}. \quad (9)$$

From this we obtain the transition jitter $\sigma_{x,Hk}$

$$\sigma_{x,Hk} = \frac{\partial x}{\partial H_s} \sigma_{Hk}. \quad (10)$$

TABLE I. Write temperature (T_{wr}) which is required to reduce the switching field to $\mu_0 H_s = 1.0$ T for three different media grain designs. The average saturation polarization at this temperature is given. The maximum AD limit due to thermal write errors is given for a BER of 10^{-2} . $\sigma_{T_{\text{wr}}}$ shows the standard deviation of the write temperature to reduce the write field to $\mu_0 H = 1.0$ T if a standard deviation of the Curie temperature T_c of $\sigma_{Tc} = 3\%$ is assumed. The resulting position jitter due to σ_{Tc} is shown for the different media as $\sigma_{x,Tc}$. For comparison, also the transition jitter $\sigma_{x,Hk}$ due to variations of the anisotropy constant is shown. $\sigma_{x,\text{tot}}$ denotes the total jitter.

	FePt	Fe/FePt–single domain	Fe/FePt–exchange spring
T_{wr} [K]	748.4	714.0	516.8
J_s (T_{wr}) [T]	0.10	1.18	1.42
AD (Tbit/in ²)	7.21	38.6	54.2
$\mu_0 dH_s/dT$ [mT/K]	270.0	18.0	3.5
$\mu_0 dH_s/dx$ [mT/nm]	4860	324	63
$\sigma_{x,Hk}$ [nm]	10^{-5}	0.15	0.79
$\sigma_{T_{\text{wr}}}$ [K]	22.5	21.8	15.8
$\sigma_{x,Tc}$ [nm]	1.25	1.21	0.87
$\sigma_{x,\text{tot}}$ [nm]	1.25	1.22	1.17

The corresponding values of the different media designs are shown in Table I, where we have assumed a temperature gradient $\partial T/\partial x = 18$ K/m, according to Refs. 19 and 20, and $\sigma_{Hk} = 0.05 \times H_k$. Here, we have assumed that the bit transition is only defined by the thermal head field gradient. In order to keep the argument as simple as possible the magnetic head field gradient was neglected since it is usually assumed to be much smaller than the thermal effective head field gradient. In Table I it is shown that indeed the transition jitter $\sigma_{x,Hk}$, which is due to variations of the anisotropy constant, is very small for the FePt media and can be neglected compared to T_c induced jitter as it will be shown below. The small jitter has its origin in the very high effective thermal head field gradient.

The second origin of jitter (ii) arises due to variations of the Curie temperature. Fig. 2 shows the switching field for different media as function of temperature. For each media two curves are shown: one for T_c and another one for $T_c' = T_c \times 1.03$. This represents a T_c variation of 3%. Due to different Curie temperatures different write temperatures are required to reduce the switching field to 1.0 T. This variation is denoted with $\sigma_{T_{\text{wr}}}$, and it is shown in Table I. Taking into account the temperature gradient $\partial T/\partial x = 18$ K/nm in the media, we now can calculate the position jitter which is introduced due to the different write temperatures T_w (which in turn are due to different T_c) as

$$\sigma_{x,Tc} = \frac{\partial x}{\partial T} \sigma_{T_{\text{wr}}}. \quad (11)$$

Table I reveals that the jitter due to variations of the Curie temperature is dominant for FePt and Fe/FePt–single phase. Interestingly this jitter is in the same order of magnitude as jitter of conventional perpendicular recording media due to variation of H_k .

The total transition jitter is obtained from $\sigma_{x,\text{tot}}^2 = \sigma_{x,Tc}^2 + \sigma_{x,Hk}^2$. It is worth noting that the best jitter performance can be obtained for the Fe/FePt–exchange spring media although it does not have the highest effective thermal head field gradient.

To conclude, a composite medium is presented which leads to a very good write-ability at high temperature and a high thermal stability at room temperature. This medium consists of different materials which are exchange coupled. The material on top has a Curie temperature slightly above the write temperature, and the other material below has a significant higher Curie temperature. It is shown that for this composite medium the thermally induced write error does not limit the achievable areal density in heat assisted recording. Recording can be performed at lower temperature which has—besides the reduced thermal write errors—several key advantages, such as an increased life time of the plasmonic transducer.²¹ Furthermore errors which occur after writing, when the medium cools down, are reduced. Optimization of the layer thicknesses of the soft layer and hard layer as well as the coupling between the layers will further increase the areal density limit. Furthermore, it was shown that transition jitter in heat assisted recording media is dominated by variations of the Curie temperature already for variation of $\sigma_{Tc} = 3\%$. Write schemes which lower the write temperature significantly below the Curie temperature are beneficial in

order to decrease the transition jitter although the thermal effective head field gradient becomes smaller.

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