Disk recording beyond 100 Gb/in.2

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Disk recording beyond 100 Gb/in.²: Hybrid recording? (invited)

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A new method for recording above 100 Gb/in.² is discussed. We call this method “hybrid recording,” a form of thermally-assisted recording that combines thermo-magnetic writing and magnetic reading. In order to increase the stability of the recorded information, writing is carried out at an elevated temperature on a medium with a very high coercivity at room temperature. In our proposal write and read heads with extremely narrow trackwidths are used, so the trackwidth is not determined by the optical spot size and the written bits have a rectangular shape, in contrast to the schemes proposed by others. Preliminary experiments are shown. The applicability of today’s granular and MO type media for hybrid recording is discussed. It is calculated that hybrid recording on optimized media can give an increase of the areal density of a factor 2.9 in areal density or 7 dB (2.2×) medium SNR improvement in case of Poisson noise and 11 dB (3.4×) in case of transition noise. Practically a factor of about 2 in density is more realistic, pushing limiting densities for longitudinal recording to 100–200 Gb/in.². Typical limitations at very high densities arise from heat dissipation in the head and thermal instability of the medium. Based on simplified model calculations including realistic limitations on medium, head and leads, and today’s practical limitations on electronics, comparisons are made between read heads containing a tunnel junction magnetoresistive (TMR) element and containing a giant magnetoresistive element with sense current in the plane (CIP-GMR) or perpendicular to the plane (CPP-GMR) of the sensor films. They show that the signal-to-noise ratio of TMR sensors for areal densities above 15 Gb/in.² is not advantageous over GMR sensors with sense current in the plane as long as the junction’s tunnel resistance is not drastically reduced to below 10 $\Omega \mu\text{m}^2$. The CPP-GMR heads are disadvantageous with respect to CIP-GMR heads until the highest densities, 300 Gb/in.², considered. © 2000 American Institute of Physics. [S0021-8979(00)85108-7]

INTRODUCTION

In the near future, both longitudinal magnetic and (magneto) optical recording will be hampered in their growth to higher densities and data rates. In conventional magnetic recording superparamagnetism will finally limit the *stable and low-medium-noise recording* of information, while in magneto-optical recording the *bit size* and *read data rate* are limited by the optical resolution and the limited Kerr rotation and allowable laser power during reading, respectively. It is generally believed that the limits of conventional magnetic disk recording of about 50–100 Gb/in.² will be reached in 4–6 years from now, because the present areal density in the most advanced products is already near 10 Gb/in.² and the present annual growth rate is over 60%. Based on simplified model calculations, the present article discusses the limits in conventional magnetic recording for various sensor types and the improvements obtainable by hybrid recording. Incorporated in the modeling and discussions are maximum sense current and signal, medium, head and electronics noise, medium requirements and the transition width, data rate and signal-to-noise ratio.

PRINCIPLE OF HYBRID RECORDING

Hybrid recording is a form of thermally-assisted recording. In order to increase the stability of the recorded infor-

mation on extremely small grains, writing is carried out at an elevated temperature on a medium with a very high coercivity at room temperature, using write heads with high-saturation flux guides and an integrated light path added to it. Local heating of the medium by laser light through the light path during writing reduces the coercivity of the medium temporarily to a value that makes recording with high-saturation write heads possible. With hybrid recording, a smaller transition width and higher density or a better signal-to-noise ratio can be obtained than those achievable by conventional recording.

In our proposal, the trackwidth is not determined by optical limits but by the submicron width of the magnetic head, in contrast to the thermo-magnetic recording scheme proposed by Katayama *et al.*,¹ and the bits have a rectangular shape, in contrast to the scheme proposed by Nemoto *et al.*² and Saga *et al.*³

Limiting areal densities, D_a , of 50–100 Gb/in.² for conventional longitudinal recording were estimated by Bertram *et al.*,⁴ based on the calculated SNR of granular media, SNR_{med} , with 10-year data life time and recordable with high-saturation write heads. In the present article, the influence of read head sensitivity and read head+electronics system noise, leading to SNR_{h+e} , is added. It turns out that, even for the best present-day sensors utilizing the highest-possible sense currents, SNR_{h+e} is of the same order as SNR_{med} and consequently has considerable influence on the obtainable maximum density. For future improvements in

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FIG. 1. A schematic representation of the experimental tester showing the disk, the head/slider combination and the complete optical system.

densities a drastic reduction of the grain size is necessary to increase SNR_{med} (via reduction of the medium noise). An increase of the saturation magnetization M_s is desirable to increase SNR_{h+e} (via increased signal flux), if the sensor's sensitivity cannot be increased further. Both measures reduce the stability of the stored information strongly, unless the anisotropy field, H_k , of the particles is drastically increased. This motivates work on media with very high coercivity and our work on hybrid recording, necessary to record on very-high coercivity media.

PRELIMINARY EXPERIMENTS

Our experimental system for a preliminary study of some aspects of hybrid recording is schematically given in Fig. 1. It shows a hard disk medium (Komag) with a glass substrate (thickness 0.8 mm; refraction index 1.6) mounted on an air bearing spindle, an inductive $\sim 2 \mu\text{m}$ trackwidth write/MR read hard disk head and a light path.

The temperature dependence of the remanence, M_r , and the coercive field, H_c , relevant for hybrid recording, have been measured by a vibrating-sample magnetometer (VSM) and are given in Fig. 2.

The medium on the side of the double-sided disk has been removed by sputter etching. The 10 mW laser light (wavelength 659 nm) was focused (through the glass substrate onto the magnetic layer) to a $0.8 \mu\text{m}$ spot with a lens with a numerical aperture of 0.45. An active focus system was necessary due to the disk waviness, which was significantly larger than the focus depth. The camera allowed the laser spot and write head to be aligned to well within $10 \mu\text{m}$. Further alignment was carried out by performing magnetic recording experiments at lower than optimal recording current and scanning an area. As an example Fig. 3 shows the

FIG. 2. Temperature dependence of M_r (dashed) and H_c (solid) of the commercial medium used in the experiments.

FIG. 3. Amplified read head output after thermally-assisted writing. It demonstrates laser and head alignment and shows the expected asymmetric thermal profile caused by moving the medium in the x direction.

amplified read head output signal after scanning over an area of 6 by $6 \mu\text{m}^2$.

The result shows the region where the medium coercivity is reduced due to the heating effect of the laser spot. The measurement was taken using a write current of only 12 mA (zero to peak), whereas the write current for optimal signal read back at room temperature was found to be 25 mA (zero to peak). The results therefore imply that the coercivity of the medium was temporarily reduced from 256 kA/m (3200 Oe) to around 120 kA/m (1500 Oe). From Fig. 2 this implies a rise in temperature of the magnetic medium of 200 K. The experiment shows the principle of hybrid recording in a conventional thin-film granular medium. For realistic hybrid recording at high densities the medium characteristics must be optimized according to the rules in the following section.

REQUIREMENTS AND IMPROVEMENTS

This section deals with the density or SNR improvement possible with hybrid recording and with the question which media characteristics are required to practically realize these improvements.

For the stability of written data, a high coercivity at room temperature and a large grain size is sufficient. A high H_c is also necessary for a small transition length. For the writability a writing coercivity below approximately 360 kA/m (4500 Oe) at the writing temperature, T_w , is necessary for writing with heads made of materials with a high saturation induction, B_s , like $\text{Fe}_{88}\text{Ta}_{12}\text{N}$, $\text{Fe}_{97}\text{Si}_3\text{N}$ ($B_s = 1.45$ and 1.9 T) or other Fe-rich alloys. A coercivity of approximately 240 kA/m (3000 Oe) provides more freedom in the choice of write head materials (common compositions: $\text{Ni}_{80}\text{Fe}_{20}$, $\text{Co}_{88}\text{Nb}_9\text{Zr}_3$, $\text{Fe}_{84.9}\text{Al}_{5.6}\text{Si}_{9.5}$ have $B_s \sim 1 \text{ T}$, and higher B_s when Fe or Co content is increased, e.g., $\text{Ni}_{45}\text{Fe}_{55}$ has $B_s \sim 1.6 \text{ T}$) or makes a smaller write gap possible, with the advantage of a slightly larger head-field gradient. These coercivities correspond typically to an anisotropy field, H_k , in case of randomly oriented grains in a granular (polycrystalline) medium, of roughly twice the H_c value⁵, viz. between 480 and 720 kA/m (6000 and 9000 Oe). For the SNR modeling further on, the conservative choice $H_k = 480 \text{ kA/m}$ is applied.

Values of M_s or M_r not higher than about $1.2 H_c$ ($0.6 H_k$) are usually to be preferred in order to avoid demagnetization and reduction of the decay time in saturated recording

at the highest linear densities and to avoid transition widening. The short-wavelength output reduction due to transition widening counteracts the larger output that an increased M_r would otherwise give. For relatively thin media with respect to the bit length, higher values of M_r are optimal. Hybrid recording introduces a new condition, viz. that the $M_s/H_c \approx M_r/H_c \propto H_{\text{dem}}/H_c$ ratio anywhere between the writing temperature and room temperature must be sufficiently low. A large ratio will deteriorate the transitions, because a relatively large demagnetizing field reduces the energy barriers for magnetization jumps in the demagnetizing field direction. Direct demagnetization or rapid thermally-activated reversals according to the Arrhenius–Néel law⁵ then take place. This has negative effects on both the short-wavelength output and the medium's transition noise. At room temperature it has dramatic effects on the storage lifetime of the remaining information according to the same Arrhenius–Néel law.

The temperature dependence of M_r/H_c of the commercially-available medium applied in the experiments, see Fig. 2, does not fulfill the basic requirement of sufficiently low M_r/H_c ratio at (and below) the writing temperature. Only at room temperature the ratio is optimal.

The question arises if there is a maximum-possible advantage of hybrid recording, assuming that media with any combination of $H_k(T)$ and $M_s(T)$ could be developed. The answer is positive and follows from the above recording considerations and Arrhenius–Néel decay:⁶

$$\begin{aligned} \left(\frac{D_{a,H}}{D_{a,C}} \right)^{3/4} &= \left(\frac{\text{SNR}_{\text{med},H}}{\text{SNR}_{\text{med},C}} \right)^{\beta} \\ &= \left(\frac{V_C}{V_H} \right)^{1/2} = \frac{H_k(T_s)}{H_k(T_w)} = \frac{M_s(T_s)}{M_s(T_w)} \\ &= \left(\frac{T_s \ln(t_s f_0 / \ln(2M_r / (M + M_r)))}{T_w \ln(t_w f_0 / \ln(2M_r / (M + M_r)))} \right)^{1/2}, \end{aligned} \quad (1)$$

where $\beta=1$ for random-particle (Poisson) noise and $2/3$ for transition noise, t_w and t_s are the decay times in seconds from magnetization M_r at $t=0$ to M at t_w or t_s , and f_0 is the reversal attempt rate. The decay times t_w and t_s must be chosen equal to the maximum total heating time at temperature T_w experienced by an arbitrary point of the medium and required storage time at temperature T_s of the medium, respectively. The subscripts H and C denote hybrid and conventional recording, respectively.

The last ratio in (1.1) determines the possible improvements in D_a and SNR (first and second ratio) and minimum hybrid-recording-medium requirements (fourth and fifth ratio). From studying the last ratio and realizing that t_s is almost 15 orders larger than t_w , it follows that the maximum density or SNR improvement is mainly determined by t_s and t_w and to a lesser extent by T_s/T_w . Realistic changes in f_0 and M/M_r are of minor importance. The third ratio, between the *minimum* grain volume in conventional recording, V_C , and the *minimum* grain volume in hybrid recording, V_H , is added for getting some feeling of the physics behind the expression. Because of the logarithmic functions in the last expression, this volume ratio is very small compared to the decay-time ratio t_s/t_w . The grain volume reduction in hybrid

FIG. 4. Areal density and medium SNR of hybrid recording with respect to conventional recording, assuming only transition noise or only random particle (Poisson) noise. The SNR is defined as a signal ratio and not as a power ratio.

recording can be used for a medium's SNR improvement or for an areal density increase. The M_s and H_k ratios in (1) indicate *minimum* conditions for an *optimal* medium for hybrid recording: this “minimal” hybrid recording medium must have a constant $H_k(T)/M_s(T)$ ratio during cooling down. Higher medium specifications cannot lead to considerably larger improvements and might even give less than the above improvements.⁶

For $M/M_r=0.8$, $f_0=10^9 \text{ s}^{-1}$, $T_w=450 \text{ K}$, $T_s=300 \text{ K}$ and $t_s=10 \text{ yr}$, the results are given in Fig. 4 as a function of t_w . A practical value for the total time that an arbitrary point of the medium is heated is $t_w=490 \text{ ns}$. This value corresponds to a realistic spot center-line heating time of 100 ns (longitudinal spot diameter $1 \mu\text{m}$ and velocity 10 m/s) and heating-up six tracks at a time (transversal spot diameter of $1 \mu\text{m}$ and a track pitch P of $0.16 \mu\text{m}$). The $0.16 \mu\text{m}$ track pitch corresponds to an areal density $D_a=100 \text{ Gb/in}^2$ for $P/B=4.27$ (using $W/g=4$, $g/B=0.8$ and $W/P=0.75$, with W =trackwidth, g =gap length and B =user bit length, viz. the shortest distance between transitions, assuming a simple non-return-to-zero, NRZI, code). A special data write architecture is needed to avoid heating longer than the aforementioned unavoidable heating during 490 ns.

According to Fig. 4, an increase of the areal density with a factor 2.2, or an increase of the medium SNR for Poisson noise of 5.3 dB ($1.8\times$) and 8 dB ($2.5\times$) for transition noise, is for this $t_w=490 \text{ ns}$ theoretically possible. Expression (1) subsequently indicates that the ideal single-layer medium for hybrid recording to make this possible, for the above choices and conditions, should have a reduction of H_k ($\propto H_c$) of a factor of 1.8 between storage temperature T_s and writing temperature T_w , accompanied with an equally-strong reduction of M_s ($\approx M_r$).

In principle there seem to be no fundamental objections to develop media for hybrid recording that fulfill the above requirements concerning M_r and H_c values and temperature dependencies. Additional calculations show that more than a factor 2.9 in areal density or 7 dB ($2.2\times$) SNR_{med} improvement for Poisson noise and 11 dB ($3.4\times$) for transi-

FIG. 5. Temperature dependence of M_r (solid lines) and H_c (dotted lines) of a double-layer MO-type medium for thermally-assisted recording. (Ref. 7). Squares (■)(□): memory layer; diamonds(◆)(◇): read out layer.

tion noise (obtained when T_w would be close to T_s and M_r and H_c are reduced by a factor of at least 2.9 between T_s and T_w) is theoretically impossible, unless $f_0 \times t_w$ could be made drastically smaller than assumed above. However, these conditions concerning $f_0 \times t_w$ and the temperature dependence are not realistic. At densities below 100 Gb/in.² the maximum improvement is slightly larger and at higher densities slightly lower. A spot size of 0.3 μm instead of 1 μm would result in an increase of SNR_{med} for Poisson noise from 5.3 to 6.7 dB.

Quite different type of media that can be made applicable for hybrid recording are MO-type media. Perpendicular MO media have been developed for writing at high temperatures. The (read-out) layers of these media have been optimized for magneto-optical (Kerr-effect) read-out. Magnetic read-out requires optimization of the M_s at the read-out temperature. Figure 5 shows the magnetic properties of a double-layer MO-type medium, adopted by Nemoto *et al.*⁷ of Hitachi to thermally-assisted writing and read out at room temperature. The magnetization of almost 300 kA/m (300 emu/cm³) of the read-out layer at room temperature is convenient for magnetic read-out. The relatively very low coercivity of the Tb–Dy–Fe–Co read-out layer itself at room temperature is compensated by exchange coupling to the Tb–Fe–Co memory layer having very high coercivity at room temperature.

A single-layer magneto-optical (MO) type of medium was optimized by Katayama *et al.*¹ of Sharp for thermally-assisted writing and reading. The compensation temperature of the rare-earth transition-metal (RE-TM) alloy chosen, Tb₂₃Fe₂₂Co₅₅, is around room temperature (see Fig. 6).

The absence of demagnetizing fields due to the compensation of the M_s of the RE sublattice by that of the TM sublattice at room temperature guarantees large storage times.

In order to assess the suitability of MO-type media for hybrid recording at ultra-high densities, thermal-decay considerations like those for single-layer conventional hard-disk type media should be applied, with modifications on (at least) two points. First, MO layers are not granular (polycrystalline) but more continuous (amorphous), and an effective activation volume will take over the role of the exchange-decoupled grains in idealized granular media. Sec-

FIG. 6. Temperature dependence of M_r (•) and H_c (□) of single-layer MO-type medium for thermally-assisted recording Ref. 1.

ond, MO media are perpendicular, and as a result the demagnetizing field decreases when the bit length decreases. Only limited experimental and theoretical work has been done on the activation volumes of MO media^{8,9} and of its possible dependence on the recording density and its meaning for transition and Poisson noise. For the Sharp medium (and also approximately for the memory layer of the Hitachi medium), assuming an activation volume definition equivalent for thermal stability to the definition of the (activation) volume of decoupled grains, a minimum activation volume of (13 nm)³ must be required for sufficient thermal stability during 490 ns total reading (or writing) time at 177 °C (450 K). For this result we further assumed $M_r = 130$ kA/m, $H_c = 120$ kA/m, $M_s = M_r$, $H_k = 2H_c$ and the maximum demagnetizing field $H_{\text{dem}} = M_r/4$ [the minimum activation volume would be (12 nm)³ for $H_{\text{dem}} = 0$]. A bit volume $Wb t_m = 122 \times 38 \times 9.5 \text{ nm}^3 = (35 \text{ nm}^3)$, with t_m the medium thickness, corresponding to 100 Gb/in.² for the parameters used earlier in this section, would occupy only 20 of these activation volumes. An insufficient medium SNR of 17 dB (7 $\times$) would result, supposing that these activation volumes are approximately equivalent to grain volumes for transition noise and Poisson noise is absent. For Poisson noise the medium SNR is only 13 dB (4.5 $\times$).

Model calculations on the granular hard disk medium from Fig. 2 with its too large $M_r/H_c = (280 \text{ kA/m}) / (150 \text{ kA/m})$ ratio at the desired writing temperature of 450 K yielded a larger demagnetizing field, $H_{\text{dem}} = M_r/2$, than assumed for the MO media. Consequently a worse medium SNR (14 dB, assuming only transition noise) resulted. These, admittedly rough, calculations suggest that for hybrid recording (much) higher H_c and M_s values as well as proper $M_r(T)/H_c(T)$ ratios are required for continuous MO type as well as for granular media.

SNR MODEL: TMR, CIP-GMR, AND CPP-GMR

A model has been made that predicts the total (on track) SNR of a high-density magnetic recording system,¹⁰ making use of current-in-plane giant-magnetoresistive (CIP-GMR), current-perpendicular to the plane giant-magnetoresistive (CPP-GMR) or tunnel-magnetoresistive (TMR) read heads (see Fig. 7). In contrast to earlier published calculations on density limits,⁴ head and electronics noise are included. For a

FIG. 7. Front view of main heat flow in shielded heads using various sensor types and having various W/g ratios. The lines indicate the direction of the heat flow. The shields are taken into account as part of the leads. The shields and leads extend in the viewing direction. The current flow is similar to the heat flow, excepted for the CIP-GMR with large W/g , where current flow is the same as for the CIP-GMR with small W/g .

certain set of model parameters, discussed below, the SNR has been calculated as a function of the areal density, D_a , assuming that the electronic bandwidth Δf increases with D_a according to $\Delta f = \Delta f_0 1.4^{\ln(D_a/D_{a0})/\ln 1.6}$ with $D_{a0} = 100$ Gb/in.² and $\Delta f_0 = 1.34$ GHz. Typically, the user bit rate is $\approx 1.5 \Delta f$. The expression reflects the wish of a 40% increase in data rate for every 60% increase in areal density. The calculations assumed a fixed ratio P/B of 4.26, consistent with the ratios $W/g = 4$, $g/B = 0.8$ and $W/P = 0.75$ that were also applied in the section "Requirements and improvements" and are assumed here, too. Figure 8 shows the results of intermediate Figs. 8(a)–8(c) and final Figs. 8(d) and 8(e) calculations, to be discussed below.

First the read heads are considered. The MR elements are in all cases assumed to contain one free magnetic layer and one layer of which the magnetization is pinned by exchange biasing. The performance of GMR elements is ultimately limited by Joule heating, which determines the maximum sense current to be used for a given acceptable temperature rise, $\Delta T_{\max}$, of the hottest part of the sensor. Joule heating has been calculated analytically for the idealized head structures shown in Fig. 7, assuming a fixed ratio, LT , between the thermal and electrical specific conductances in the metals (with $L = 2.45 \cdot 10^{-8}$ W Ω K⁻², the Lorentz number). For CIP-GMR elements heat flow is predominantly to the leads when W/g is very small.^{10,11} The (effective) thermal conductivities of the gap oxide, CIP-GMR stack, leads and shields assumed are 1, 13, 25 and 25 Wm⁻¹ K⁻¹, respectively. The CIP-GMR stack thickness is 16 nm. The MR element's sheet resistance is 40 Ω and the lead and shield resistivities are 25 $\mu\Omega$ cm. For these parameter values, and for the bit aspect ratio $P/B = 4.26$ used, conduction to the leads and to the shields are found to be of comparable magnitude for the entire areal density range considered. The heat flow is thus intermediate between those depicted for the two extreme cases in Fig. 7. The SNR calculations are carried out for a MR ratio $\Delta R_{\max}/R = 0.1$ for the CIP-GMR. The MR ratio and resistance times area produce, R^* , for the CPP-

FIG. 8. Results of SNR calculations on hybrid and conventional recording for various sensor types in shielded heads with $W/g = 4$ as a function of areal density, assuming realistic material parameters and, as yet, unrealistic dimensions.

GMR element are only $\Delta R_{\max}/R = 0.026$ and $R^* = 0.031 \Omega \mu\text{m}^2$, respectively. These values were estimated on the basis of realistic values of the spin-dependent bulk and interface resistances for a realistic layer stack (spin-valve, i.e.,

single pinning, pinned and free layer; a periodic stack gives a much higher MR ratio at the cost of a much smaller magnetization rotation). The temperature gradient within the CPP-GMR stack and TMR stack is neglected. The performance of TMR elements, with presently reported best values of R^* of the order of $100 \Omega\mu\text{m}^2$, is limited by the decrease of the MR ratio with increasing bias voltage. Calculated results for such a junction with a fixed R^* value ($100 \Omega\mu\text{m}^2$) are labeled "TMR-R". If future developments would make it possible to create junctions with much lower R^* values (e.g., due to thinner barrier layers), the sense current can be increased until it is limited by Joule heating. Calculated results for such junctions, with an optimally chosen R^* (of almost $10 \Omega\mu\text{m}^2$ at 15 Gb/in.^2 , gradually decreasing to below $4 \Omega\mu\text{m}^2$ at 300 Gb/in.^2) and operating at a fixed temperature above ambient, are labeled "TMR-T". This idealized TMR head has such a low R^* that the power V_{opt}^2/R in the sensor and direct environment causes the maximum allowable temperature rise, assumed to be 50 K, in the center of the TMR sensor. For both TMRs, $V_{\text{opt}}=0.4 \text{ V}$ and $\Delta R_{\text{max}}/R=0.1$ at this bias voltage are assumed.

Figure 8(a) shows the calculated maximum possible head SNR, when the head would be driven to saturation. Thermal noise in the MR element and in the inevitable parts of the leads (as shown in Fig. 7) has been included, and for TMR elements shot noise has been included.¹² The maximum temperature rise in the sensor above ambient temperature, $T_a=293 \text{ K}$, is assumed to be $\Delta T_{\text{max}}=50 \text{ K}$, and the thickness, saturation magnetization and relative permeability of the free magnetic layer assumed are $t_{\text{mre}}=5 \text{ nm}$, $M_s=800 \text{ kA/m}$ and $\mu_{\text{r-mre}}=1000$, respectively. The sensor height is taken equal to half the flux decay length, $\lambda_{\text{decay}}=\sqrt{(\mu_{\text{r-mre}}t_{\text{mre}}g/2)}$, of the transmission-line structure formed by sensor and shields. This choice is a compromise between domain stability, side reading and sensitivity. The results in Fig. 8(a) show that the GMR and TMR-T head have more than sufficient SNR for signal recovery when the whole dynamic range would be utilized.

In Fig. 8(b) the actual amount of flux from a fictitious longitudinal hybrid recording medium and the efficiency of the (shielded) head, as calculated using standard recording theory, are taken into account. The medium is assumed to have (at room temperature) twice the H_k and M_s of a realistic medium for conventional recording, viz. 960 and 600 kA/m, respectively, as discussed in the section "Requirements and improvements". The medium thickness, t_m , and head-medium distance, d , are assumed to be $B/4$ and the ratio between remanence and saturation $M_r/M_s=0.9$. Comparison with Fig. 8(a) shows that the sensors are driven close to saturation only at the lowest displayed density of 15 Gb/in.^2 . The amount of flux from the medium decreases as the density increases due to the decrease of the medium thickness assumed in the calculations. [For a constant thickness the reduction would be at least as dramatic. For this case the reasons are an increasing transition width with density caused by increased demagnetization ($H_{\text{dem}}\sim t_m/$

$B\sim 1/B\sim D_a^{1/2}$) at constant medium thickness and an increasing thickness loss, i.e., the part of the medium's flux that leaves the medium, approximated by $(1-e^{-\pi t_m/B})/(\pi t_m/B)$, decreases.]

Figure 8(c) shows the effect of the inclusion of noise of leads and electronics. The lead resistance is assumed to be 10Ω and the amplifier's equivalent noise voltage and noise currents at the input are taken to be $0.55 \text{ nV/Hz}^{1/2}$ and $10 \text{ pA/Hz}^{1/2}$, respectively. This drastically decreases the SNR of the CPP-GMR head with its very small resistance and hence very small signal voltage at low densities due to its small R^* . TMR-R heads can, for the densities considered, not compete with CIP-GMR heads and TMR-T heads. At high densities in particular, the high tunnel resistance of the TMR-R due to its large R^* leads to a high (shot) noise voltage level.

The medium noise is estimated from the minimum-allowable grain size⁶ (see also section "Requirements and improvements"), assuming only transition noise in granular media. Therefore, the increase of the medium SNR in hybrid recording on the aforementioned granular medium with doubled H_k and M_s [see Fig. 8(d)], is 9 dB with respect to conventional recording, [see Fig. 8(e)]. For Poisson noise this would be 6 dB. The medium SNR for conventional recording is about 1.2 dB lower than reported by Bertram,⁴ due to a slightly more conservative estimation in our simplified transition noise model.

The medium noise and sensor+electronics noise are of the same order for the CIP-GMR and TMR-T [see Fig. 8(c)]. Medium noise brings the results obtained with the CIP-GMR and TMR-T sensor types closer together [see Figs. 8(d) and (c)]. The TMR-R and CPP-GMR results are still dominated by noise from head and/or electronics. A further increase of M_s , or of the sensitivity of these sensors, will hence be necessary to reduce the influence of SNR_{h+e} on SNR_{tot} .

Even with hybrid recording using the above assumed hybrid recording medium and the best sensor specifications of today, 300 Gb/in.^2 is clearly too large: the bit error rate at 10 dB SNR is too low for today's bit detectors and error correction codes.

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