Abstract
Vertical recording can be expected to be the data storing technology for very high density recording of the nineties. At present there seems to be a gap between established longitudinal drive technology and new head concepts, improvements in substrate and coating techniques are emerging and can accelerate product developments. Vertical recording is the technology, which is predestinated by its physical nature to satisfy demands for higher and highest bit densities. Some of the new concepts and key design parameters are discussed.

Introductory Remarks
Since the introduction of vertical recording by IWASAKI about ten years ago many papers on basic concepts, media and head developments have been published and many tests have been carried out to find the point of crossing-over between the longitudinal and vertical technology. Up to now no real breakthrough of vertical recording has been observed and we are just looking at the first steps into a new technology. Or might simply be that the old longitudinal technology is fighting back and vertical recording may emerge at higher bit densities than has been expected some years ago.
Nevertheless there is no doubt that at bit densities in the range of 30 to 50 kbpi vertical recording is distinctly different from longitudinal recording. This means smaller transition widths and higher densities will be possible with vertical recording.

From this it can be concluded that getting higher linear bit densities requires distinct, cost effective and extraordinary efforts concerning heads, disks, data channels and drive mechanics.

This leads to the assumption, that vertical recording might be the better choice for the near and long term future. Two factors delaying the implementation of vertical technology should be pointed out. The one is the big innovation of glass disks as substrates for longitudinal disks, which enables lower flying height below 0.1 µm, and therefore may extend the period of longitudinal recording; and according to general experience it is unusual to insert two fundamental new concepts, namely glass disks and vertical technology at the same time. The other delaying element is that vertical recording is distinctly different to the longitudinal one in both the head design and the medium materials, structure and magnetics. These are the tools for the physics behind design. Successful work at this early step saves electronics and gives error margins.
Therefore the following considerations are mainly concentrated on head and medium design parameters.

Basic Concept
Just to recall to mind Fig 1 demonstrates some characterizing features of longitudinal and vertical recording. The longitudinal disk comprises a thin, about 50 nm thick, magnetic layer on a hard, non magnetic underlayer of about 20 µm in thickness, whereas the vertical disk consists of nearly equally thick, about 250 - 350 nm, storage layer and a soft magnetic underlayer, all resting on aluminium or glass substrate.

The basic idea that vertical recording can lead to higher bit densities than longitudinal recording is derived from micromagnetic arguments. For high bit densities the demagnetizing fields at the transition between oppositely magnetized regions are higher in the case of longitudinal and lower in the case of vertical recording. This means smaller transition widths and higher densities will be possible with vertical recording.

Thin film heads are the best choice for high performance recording, but for vertical recording properly designed ring type heads or single pole heads like the one presented in Fig 1 are needed. Additionally a keeper layer seems to be useful as low resistance flux return path.

Fig 2 shows typical head field distributions of a ring head and a single pole head for both recording modes. Roughly arguing that the output waveform follows the head field shape, then Fig 2 reveals the bipolar response of vertical recording with ring heads.

Head-medium coupling
The interrelation between head and medium is basing on strength and shape of the head field.
The waveform of the readback pulse corresponds to the gradient of the magnetic transition and the head field profile. If the field shape approached a Delta-function, the output waveform would represent the shape of the gradient of the magnetic transition. Therefore steep head fields and sharp transitions in relatively thick films are the most important key parameters for high density vertical recording.

Recording

Theoretical and experimental studies (1), (2), (3) on different head types like ferrite or thin film ring heads or single pole heads seem to confirm that a magnetized rod on a double layer medium is a better solution than any combination of ring heads with single or double layer films. This is true for a head design, which so far has been created for longitudinal recording. But it is no longer true for thin film ring heads which are designed for vertical recording exclusively.

Fig 3 gives an example. It shows the calculated head field profiles of a well known longitudinal thin film ring head (4) and a newly designed "vertical thin film ring head" (5).

The head of Fig 3a writes with the trailing edge of the trailing pole producing a relatively flat writing field shape by its long ranging tail, which ends up in broad transitions. In contrast to this the head in...
Pig 3b is designed for enhanced field strength of the leading pole $P_1$ by increasing the write current to such an extent that the trailing pole $P_2$ becomes nearly or fully magnetically saturated. The resulting field profile is extremely steep at the trailing edge of the leading pole $P_1$. This is a new type of a quasi single pole head.

It can be imagined that with increasing write current this head switches from the ring mode to the single pole mode for writing and back to the ring mode for reading. Therefore it has been called 'switching head'. Because of the missing long ranging tails of the writing edge the writing field gradient of this head is higher than the one of a single pole head; consequently sharper magnetic transitions are expected to be written.

It can be concluded from finite element (6) calculations that the field drops off to zero within nearly a gap width distance. To realize such a head design some tailoring work will be needed.

To get different magnetic saturation levels of the leading and trailing poles cross-section variations, different permeability numbers or variations in material compositions are desirable tools.

As a general advantage it may be considered, that the well known production technology of thin film heads remains common to longitudinal heads and to the new vertical ones as well. The switching head shows one way to step closer to high writing field gradients.

At this point magnetoresistive heads (MR-Heads) should be mentioned, because they seem to offer a chance for the elongation of the longitudinal period because of their high sensitivity. They might become a longitudinal and a vertical choice as well as a high end of magnetic recording. The ability of "MR-Heads" to write wide and read narrow in terms of track width is also attributed to switching heads. Depending on thin film structuring technology the leading pole $P_1$ is wider by about 2 to 4 μm than the trailing pole $P_2$. Therefore in the writing mode of the switching head the wider pole $P_1$ is active, whereas in the ring type reading mode the narrower field width of $P_1/P_2$ is decisive. The benefit is a lower side fringe reading in contrast to single pole heads or longitudinal ring heads.

**Magnetic transitions**

Writing sharp transitions is not only a question of head field gradients. The magnetic response of the storing layer has to be considered and this is completely different to longitudinal recording (Fig 1). After calculations of (7),(8),(9) et al vertically recorded transitions are asymmetrical in shape with an over-shoot on the trailing side of the transition center, or eventually on both sides if we look at a more idealized situation which may be approached at very high densities (3).

Fig 4 gives an example for calculated transitions.

**Readback Waveform**

Under the aspects of low bit shift (peak shift), low bit error rates and high phase margins it is most desirable to come out with symmetrical bimodal isolated pulse waveforms in the case of ring heads or with undershoot-free waveforms in the case of single pole heads. Fig 5 offers the principal solution for both types of heads. After Fig 5a the situation of single pole heads seems to be simple and clear, provided that the auxiliary pole, designed as flux return path, is some μm distant to the main pole and do not show "edge-reading" effects. But it is unanswered what the readback waveform is like at lower flying height or higher bit densities, where we are facing transitions with an overshoot. There is an answer to this question in the case of a switching head, which is demonstrated in Fig 5b for high bit densities. More principally speaking the above mentioned tools for tailoring optimized switching properties are not only just useful but they are needed for adaptation of the head field profile (unsaturated state) to the shape of the
Fig 5 Schematic representation of vertical magnetic transitions plus wanted, to be designed head fields and resulting optimum output waveforms.

magnetic transition. Moreover the bimodal shape of the ring head output has the benefit of an "a priori" zero crossing for signal detection. No differentiation has been done.

It should be noted that the tool of finite element calculation is becoming more and more the basic design tool in the race of getting higher and higher bit densities. Finite element calculation is a key design parameter preferably of vertical recording.

The storage layer

From a physical point of view there are many alloys which are suitable for vertical recording. The anisotropy field $H_a$ has to be stronger than the saturation field $H_s$, enabling stable vertical orientation of the easy axis of magnetization. CoCr-compositions have always been the favorite materials and have been studied at best until now. It serves as an example here. Fig 6 shows a magnetization loop $M(H)$ of a CoCr-film with 20 wt% Cr.

Fig 6 Magnetization loops of a CoCr film measured with a VSM.

It represents a magnetic layer with infinite lateral extensions. After that a writing field strength of $>2H_c$ ($H_c$: coercive force) is needed for overwriting the remanent field of $M_r$. But for a written bit pattern the demagnetizing fields are lowered and consequently the local magnetization loop is somewhat desheared, at least at very high densities. One impressive experimental evidence for this type of deshearing of magnetization loops has been reported by (10) for contact recording. The picture reproduces electron holographic interference micrographs of vertically recorded transitions. The authors could figure out a maximum local magnetization that was about three times higher than the remanence measured with a vibrating sample magnetometer. The in contact recorded density reported in Fig 7 corresponds to about 100 kfc. This is further experimental evidence, that vertical recording can provide enhanced magnetic data and improved magnetic stability of the transitions especially at very high bit densities and lower flying heights.

The keeper-layer provides further deshearing in actual read/write processes. It acts as the counterpart of the head and because of its contact to the bottom of the storage layer, it reduces the stray field by offering a low resistance flux path. Thus we can expect higher $M_r$ values with keepered films.

Fig 7 Electron holography interference micrograph of a vertically recorded CoCr-film with 20 wt% Cr.

transition distances: 0.25µm
film thickness: 0.35µm, track width: 70µm

In practice the designing of a vertical disk requires the optimization of some magnetic and/or crystallographic key parameters. A few of them should be mentioned here. For vertically anisotropic films the easy axis of magnetisation, which is bound to the $c$-axis of the hexagonal crystal structure, is vertically to the film plane. For receiving high anisotropy it is necessary to keep the deviations from the vertical orientation below a rocking angle of about 3°. To realize this an intermediate layer between keeper and CoCr-film is obviously useful (11,12). It serves as nucleation layer for improved growth of the CoCr film on the keeper. As an example, a Si seed layer of 30 nm thickness is sufficient to improve the crystal
orientation significantly (13). Further improvement can be gained by preheating the substrate up to temperatures of about 150 °C. The combination of seed layer plus preheating is the most effective procedure.

The next point to be considered is the relationship between methods of film production, substrate temperature, type of keeper or nucleation layer, film thickness, film composition etc. on the one side and magnetic data or read/write data on the other side. Because there are some hundred papers concerning these items, only a short report on trends can be given here.

The following data correspond to switching head/CoCr-media combinations, but they are of general meaning.

![Graph](image)

**Fig 8** Normalized VTA vs frequency (Roll-off curve), pulse crowding of the bimodal pulse shape, switching head on double layer CoCr.

![Graph](image)

**Fig 9** Switching head, double layer medium.

**Fig 8** represents a typical roll-off curve of a CoCr-film with data recording and retrieving by a switching head at a flying height of 0.2 µm. The micrographs, partly overlaying the roll-off curve, demonstrate the pulse crowding effects with increasing bit densities.

Overwrite ratios and S/N-ratios for such head-medium combinations are > 30 dB. With RLL codes recording densities of about 100 Mb/1² are conceivable. Fig 9 gives a representation of what can be gained by reducing the flying height. Fig 10 gives some trends in the relationship between readback voltage, OW-Ratio, S/N-Ratio and coercive force. Like with longitudinal recording the coercive force deserves most attention, it is a dominating parameter.

![Graph](image)

**Fig 10** Trends of VTA,OWR,SNR of double layer CoCr films versus the dominating magnetic parameter Hc and substrate temperature.

Because of the much larger thickness of vertical films the third dimension should be taken into account. A matching of head field shapes to different Hc values throughout the film thickness is conceivable, i.e. high Hc values near the head facing surface and low Hc values near the opposite one would fit to accordingly high and low field levels. Higher readback voltage and narrower pulse shape are expected. But up to now experimental tests did not reveal any reliable improvements.

It is obvious, that the operation conditions during the most favoured sputtering process play a major roll in getting optimised structural and magnetic film properties. As an example the degrading effect of too a high background pressure, mainly nitrogen and oxygen components, on some magnetic data may be mentioned (14). Hk and Hc reduce rapidly with increase in nitrogen content above a partial pressure of 2*10⁻⁶. A similar situation is given at oxygen partial pressure of the same order of magnitude. Solely hydrogen seems to have no marked influence, according to our own experience too.

**Head-Medium Interface**

The reduction of flying height offers not only positive aspects; the mechanics of the interface of head and disk during stats/stopes and flying operations are to be payed strong attention. Roughly speaking there are two competing processes. On the one hand carefully lapped and polished surfaces should be provided for enabling low
flying heights, on the other hand the adhesive strength between the two surfaces increases with increasing smoothness causing slider rails and disk surfaces attracting each other more strongly in cases of head-medium contacts. Surface damages and data losses can happen. At present no other solution than coating with friction reducing layers seems realistic.

The additional function of protection against corrosion can be neglected under non-aggressive, clean, dust-free ambient conditions, because CoCr compositions with more than about 15 wt-% Cr form selfpassivation layers of chromium oxide. It is favourable to sputter pore free protecting films, which are impermeable to water and metallic ions. An additional measure against corrosion is to apply higher Cr contents (above 15 wt-%), which helps to resist corrosion very effectively (15).

New developments of glass surface finishing methods by chemomechanical etching facilitate flying heights below 0.1 μm. Glass can be hardened by ion exchange in the near surface region and by this it eliminates the otherwise needed hard intermediate layer known from aluminium substrates. Fig.11 gives an example of experimental results of start/stop tests (CSS) carried out with an antifriction layer on a double layer CoCr film on a polished and hardened glass substrate. The static and dynamic friction coefficients are well below 0.5, quite a good result for practical usage.

References

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