Recording heads: write heads for high-density magnetic tape

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ABSTRACT

A review of the performance requirements for the writing components of high density tape recording heads is given in the context of multichannel linear tape head arrays. A brief tutorial of head operation is given. This is followed by a discussion of pole materials and head array architectures. Technical advances which have lead to increases in data rate and recording density are identified.

Keywords: tape recordings heads; recording heads; tape recording; high density recording; recording; tape head arrays; pole materials; head design; heads;

1 INTRODUCTION

This paper will treat recent advances in write heads for high density tape recording heads. As these proceedings deal with enabling technologies for the information infrastructure, digital data storage will be the focus of this paper. Digital data storage on tape is dominated by "linear" formats like the 3480-type and Quarter-Inch-Cartride (QIC) rather than "rotary" formats like the standard VCR. This is due to the larger data rates which are possible in multichannel arrays; and in fact rotary digital recording formats do exist in arenas like audio recording where fidelity is more important than data rate (e.g. RDAT). Consequently, this paper will concentrate on the multichannel write transducers most often used in these types of recording systems. Readback in these systems is usually accomplished with magnetoresistive (MR) elements which are the subject of a separate paper in these proceedings. This paper begins with a brief review of head geometry and head operation during the write process. This is followed by a discussion of pole materials and head array architectures. Advances in both of these areas continue to drive improvements in head performance.

Arrays of tapes heads used in linear tape recording have been used for a several decades, and they have enjoyed steady improvement in performance. Originally constructed of machined ferrites with wound wire cores, they have evolved into devices which have incorporated photolithographic techniques, first for the fabrication of coils,[1] and then, as thin film poles became necessary, for the definition of poles as well,[2] undergoing dramatic reductions in size along the way. The basic features are still identifiable, though, and can be seen in Figure 1. The heads have an array of magnetic pole tips in a line perpendicular to the tape motion, separated by a non-magnetic gap, and a tape bearing surface which is contoured to facilitate good contact. The head shown is consistent with the construction method of thin film tape heads, in which a device is fabricated on a wafer, and then covered with a second wafer - the cover plate - attached by glue. Not shown is the parallel row of MR elements which would be present in a typical commercial head today. They would be fabricated as a separate wafer and cover plate

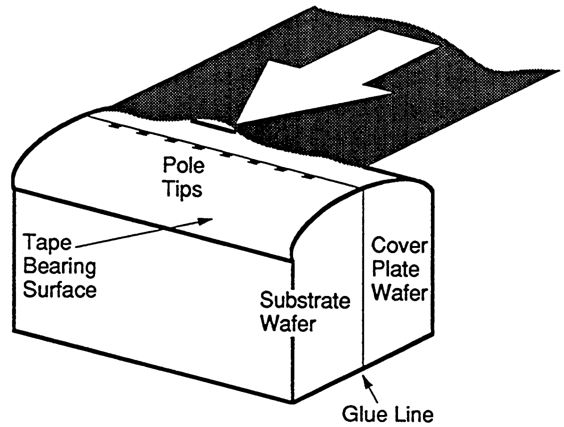

Figure 1: The generic form of a thin film linear tape head array, showing the contour and array of pole magnetic pole tips at the tape bearing surface. The substrate, glue line, and cover plate are also indicated.

assembly, and attached with an additional glue joint.[3]

2 WRITE HEAD OPERATION

2.1 Written transition sharpness

During the writing process, the head produces a field in the gap between the two poles, termed the deep gap field, H_g. At this gap, fringing fields from the poles extend into the tape, and produce the recorded transitions as the fields are switched. Typically, these transitions follow the $H = H_c$ contour of the head fringing field, as that is the value of applied field at which the medium magnetization switches.[4,5] A schematic of this geometry is shown in Figure 2, indicating the typical field contour shape.[3]

In digital recording, this transition represents a "1", and therefore directly represents the information being stored (the absence of a transition represents a zero). The spatial localization of the transition - the distance over which the magnetization switches from plus to minus - represents the limit on the recorded information density. Additionally, at a fixed tape speed, this transition length represent the limit on the data rate.

The sharpness of this transition is determined by its tendency to demagnetize, or erase, itself. This tendency can be reduced by reducing the ratio $M_r t/H_c$, where M_r is the media magnetization, t is the media film thickness, and H_c is media coercivity, which is the applied magnetic field required to switch the magnetization of the tape.[3] Reducing this ratio will result in one of two challenges for head designers. Decreasing the ratio by reducing $M_r t$ cuts down the signal available for readback, placing increased sensitivity demands on the read head. Conversely, decreasing the ratio by increasing H_c places a burden on the write head to produce larger recording fields. Generally, improvements in both head are sought, but in this paper we will consider only the demands for more field placed on the write head.

Although more complicated treatments of the above material are possible (a number of excellent textbooks treat this theory in detail[3,5–7]), the conclusions remain the same. Recording on media which will support higher densities and consequently higher data rates will, in general, require a higher write field. A rule of thumb is that

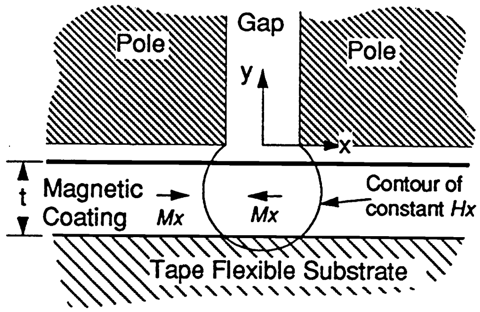

Figure 2: A schematic of the fields emanating from a pole tip and fringing into the recording medium. The circle shown represents a contour of constant H_x, which is the component of field in the direction of tape motion, and the field component which does the recording. In the simplest approximation, this also defines the location of a written transition.

H_g should be at least 3 H_c to insure adequate media saturation, correct transition location, and adequate write field gradient.[5] Bertram[8] has suggested that continued improvements accrue up to deep gap fields as high as 3.5 H_c on thick recording media.

2.2 Head saturation and efficiency

Deep gap fields cannot, in theory, exceed the saturation induction of the pole material at the gap. Furthermore, in practice, good head performance is limited to the regime where H_g is substantially less than the saturation induction, due to local points of saturation within the head. How much less is a matter of some debate. Estimates of around 60% are common.[5] This indicates that the pole material controls the amount of field the head can generate - a higher saturation induction indicates a higher H_g. The quest for higher and higher moment pole materials has lead to continuing developments of new materials which are discussed below in Section 3.

In addition to producing a given magnitude of field, the head must be able to deliver the field at a reasonable drive current, to limit heating, power consumption, coil complexity, etc. A recording head is a magnetic circuit, and as such, an analogy can be drawn between it and a more familiar electrical circuit (this is also treated in some of the references on head operation[7]). The magnetic flux which the poles carry is analogous to electrical current. The analogy to the voltage or electromotive force of an electrical circuit is the magnetomotive force, NI, in a recording head, where N is the number of coil turns threading the magnetic path, and I is the electrical current carried by each turn. This is shown schematically in Figure 3. The field in the gap, H_g (in A/m), is then given by:

$$H_g = \eta \frac{NI}{l_g} \tag{1}$$

where l_g is the length of the gap in the downtrack direction (in m), and η is the head efficiency, a number between zero and one which indicates how much of the magnetomotive force shows up across the gap. It can be calculated in the same way as for a voltage dividing circuit, such that:

$$\eta = \frac{R_g}{R_c + R_g} \tag{2}$$

where R_g is the reluctance of the gap, and R_c is the reluctance of the core. Analogous to electrical resistance,

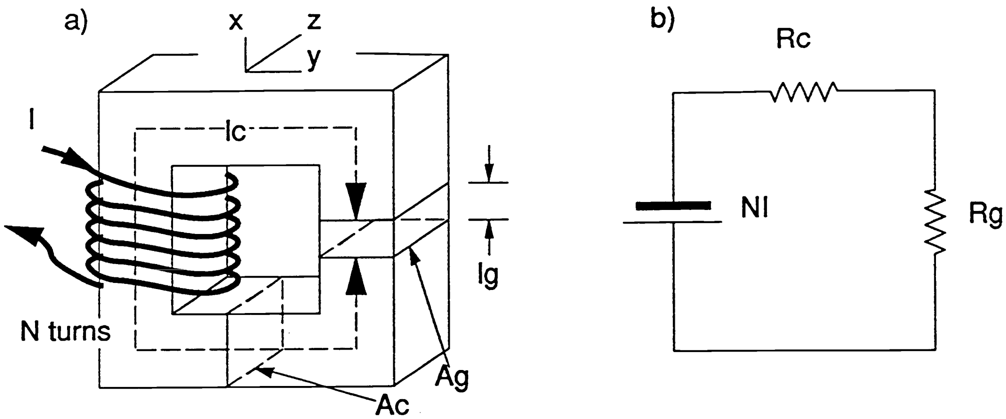

Figure 3: a) A schematic of the head magnetic circuit and b) the simplest electrical analog.

the reluctance of the ith element is defined by:

$$R_i = \frac{l_i}{A_i \mu_i} \tag{3}$$

where l_i, A_i, and μ_i are the length, cross sectional area, and permeability of the ith circuit element. The analogy to electrical resistance is retained in this definition, with permeability playing the role of conductivity. Finally, then, the efficiency can be written as:

$$\eta = 1/\left(1 + \frac{l_c A_g}{l_g A_c \mu_r}\right) \tag{4}$$

where the subscripts c and g refer to the core and the gap, respectively, and μ_r is the relative permeability of the poles, compared to the permeability of air.

For a typical head, the dimensions might be as follows: $l_c = 200\ \mu m$, $l_g = 1\ \mu m$, $A_c = 100\ \mu m^2$, and $A_g = 50\ \mu m^2$. These values give an efficiency of 95% for a relative pole material permeability of 2000. In fact this number is unrealistically high, as no account has been taken of field leakage between the poles. A more sophisticated analysis is possible using transmission line analysis to calculate the performance of more realistic structures.[9,10] Such a structure and its equivalent circuit are shown in Figures 4b) and a), respectively. The results of the efficiency calculation are shown in Figure 4c). The efficiency gets to 85% at permeabilities of 2000 in this model of a head with relatively thick poles. A conservative rule of thumb for design is about 75%. In practice, efficiencies above 75% are not achieved unless the poles are made very thick,[10] which presents fabrication difficulties.

Several phenomena can interfere with high pole material permeability during head operation, thus lowering the head efficiency. A high intrinsic permeability can be reduced by magnetostrictive effects, through which the direction of magnetization and the film stress interact.[3] Permeability of patterned devices tends to be best when the saturation magnetostriction is as small as possible. A good rule of thumb is that the elongation in going from the demagnetized to the saturated state should be kept smaller than 1 part per million.

Permeability at high frequency can also be reduced by eddy current losses, which says that higher resistivity pole materials are generally better. Eddy current losses are not an inordinate concern in sputtered metal films, however, as laminations with thin insulating layers can be used to improve the frequency at which eddy currents undermine the permeability.[11] Additionally, pole shape can effect the magnetic domain structure within the pole,

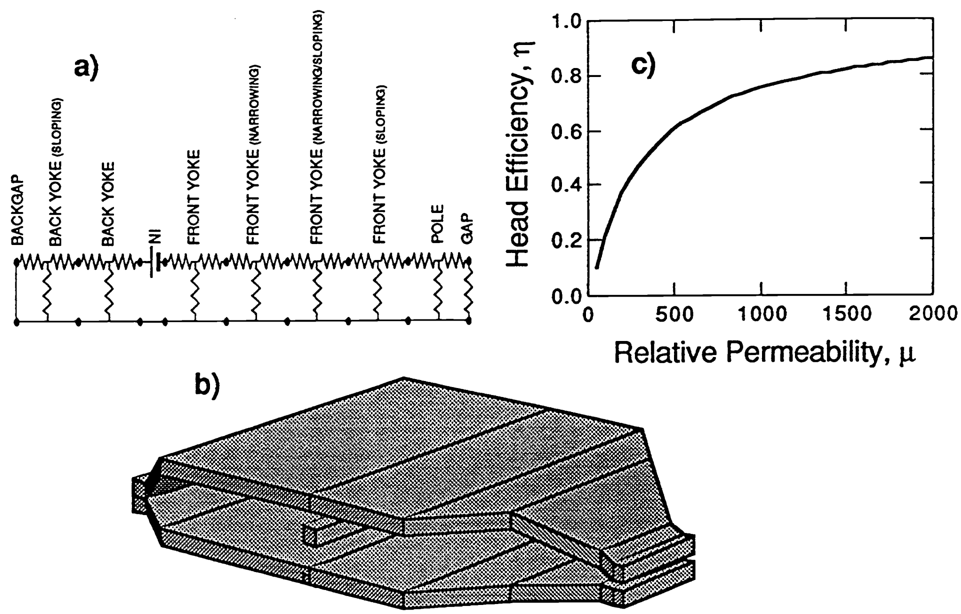

Figure 4: The equivalent circuit, a), for a more realistic pole structure, b). The efficiency, η, of such a structure as function of pole material permeability is shown in c).

dramatically reducing permeability. Some workers have undertaken detailed studies to understand the interaction of pole shape and laminations in producing domain structures favorable to high permeability at high frequency.[12]

2.3 High density example

At present, the media offering the best combination of magnetic properties, commercial availability, and corrosion resistance is thin coat, metal particle (MP) media, developed for video recording. This tape is produced by a double coating process in which the top 200 nm of the coating is magnetic, and the rest (another 1-2 μm of non-magnetic coating) is there to smooth out the imperfections in the substrate surface. Other media, like Ba-ferrite (BaFe) and Metal-evaporated (ME) media, can also be obtained with excellent performance, but the commercial trend is, at present, toward double coat MP media. These media will soon have commercially available coercivities of 2000 Oe, which, in combination with $M_r t$, should support 100 KFCI (kiloflux changes per inch). Taking the 60% factor to avoid pole saturation, and the factor of 3 H_c to insure media saturation, yields a required pole material saturation induction of 10 kG. Continued improvements might be seen up to values of 14 kG. Data rates of 100 Mbits per second distributed over 16 channels would require a carrier frequency of approximately 3 MHz, and no roll-off in head response until frequencies above 50 MHz, to give high fidelity pulses.

3 ADVANCED POLE MATERIALS

3.1 Requirements

Pole material performance is perhaps the single most important determinant of head performance. The extent to which the pole materials meet the stringent demands placed on them, is the extent to which the head functions. Magnetically, the pole material must have high magnetic moment, and high permeability under the operating conditions. As shown above, to meet the goal of recording on 2000 Oe media, the lower limit on pole material magnetization should be 10 kG, with 14 kG offering a good margin of comfort. Relative permeabilities above 2000 are desirable for efficient head operation, but values down to 1000 might be tolerated as a trade-off for some other desirable property. This value must be retained to beyond 50 MHz. Mechanically, the pole should be as resistant to wear as possible. Wear causes signal losses and reduced field gradients because of the increased spacing between the tape and the head. It also can result in debris generation, which further degrades the head-tape interface. It has been shown that coating the head surface can dramatically improve wear,[13] but the coating may result in an unacceptable level of spacing loss. In terms of process compatibility, the material must not require high processing temperatures (above 250°C), but should be thermally stable, have good adhesion, etc. Susceptibility to corrosion is also a factor, as the head-tape interface is a corrosive environment. Table 1 shows a list of pole materials which have been used or proposed for use in thin film recording heads. Each of these will be given a brief evaluation below, on the above criteria. This section was distilled, in part, from some excellent reviews of pole materials.[14–16]

Table 1: A summary of the pole materials in use or under development, adapted from the review articles.[15,16]

Material Family	Examples	Saturation Induction (kG)	Relative Permeability (DC)
Ferrite	MnZn, NiZn	5	1000
Permalloy	$Ni_{80}Fe_{20}$	10	2000
Sendust	FeAlSi, FeRuGaSi	11-12	1500 - 2000
Co alloys	CoZrNb, CoZrTa	12-15	1000 - 2000
Fe Nitrides	FeN, FeAlN, FeTaN	18-20	up to 3500

3.2 Ferrites

Ferrites have been used extensively in tape heads, as well as in video recording heads. Their appeal is that they can be machined as a macroscopic entity and still avoid eddy currents due to their insulating nature. They are limited in their ability to generate fields in the gap by a low saturation magnetization of 5 kG. These materials currently cannot be sputtered as thin films, although there is work in this area. These combination of properties suggests that their contribution is limited to a bottom pole configuration, or as a metal-in-gap configuration, where a high moment material lines the gap to allow the generation of higher fields.[16]

3.3 NiFe (Permalloy)

The alloy, $Ni_{80}Fe_{20}$, possess all of the necessary properties to be used as write head poles, and has, in fact, been the industry standard for thin film poles for thirty years. It can be made with vanishingly small coercivity, relative permeabilities greater than 2000, zero magnetostriction, and can be cheaply and rapidly electroplated, as well as sputtered. Magnetically, however, due to its saturation magnetization, its performance envelope barely extends to 2000 Oe tape media. Therefore, there is a strong drive to replace this material with a higher moment material. Furthermore, although it has been used extensively in recording heads for rigid disk heads, it is too susceptible to wear to be an acceptable pole material for high density tape recording.[14]

3.4 Sendust

Sendust (FeAlSi) was seen as an alternative to permalloy which was much more wear resistant, but its moment is barely any higher, which limits its desirability as a pole material. Early problems with sensitivity to composition variations led to the development of Sofmax, FeRuGaSi, which has the same wear resistance, but is much more tolerant of compositional variation, and has a somewhat higher moment.[14,16] A major concern however, is that the processing temperatures needed to realize soft properties in these materials are rather high (up to 500°C).[17] This makes them unacceptable for thin film head processing where hard cured photoresist forms part of the head structure.

3.5 Amorphous Co Alloys

Amorphous alloys of Co, like CoZrNb and CoZrTa, offer a higher moment alternative to permalloy, and are currently used in some commercial heads. These materials offer a somewhat lower permeability, but still high enough to produce reasonably efficient heads. Careful attention must be given to thermal treatment, as the easy axis of magnetization can be rotated with field annealing at, by thin film head processing standards, rather modest temperatures.[14] In some cases, processes have been completely changed in order to avoid exposing these films to the 250°C temperatures associated with photoresist hardcuring process.[2] If some reduction in moment can be tolerated, better thermal stability can be achieved.[14] Despite these limitations, it is fully expected that these materials will be adequate to record on 2000 Oe MP media. There is some question as to how much farther they can go in terms of media coercivity. Certainly, they will run out of flux before the 3000 Oe media mark.

3.6 Fe Nitrides

The Fe nitrides, with their saturation magnetizations of up to 20 kG, offer the potential of writing on media with coercivities up to and beyond 3000 Oe. Films of FeTaN and FeAlN can be made with soft as-deposited properties, reducing the necessary annealing temperature to one consistent with photoresist hardcuring.[18,19] Their ability to write on 2000 Oe media has been demonstrated conclusively.[20] In fact, their ability to write to thin media with coercivities up to 3800 Oe has been demonstrated in rigid disk recording.[21] The challenges associated with commercializing these materials amount largely to processing issues. Where the amorphous Co family is sputtered in Ar, the FeN family is reactively sputtered in N_2 and Ar. This presents additional challenges on process control, as they display sensitivity to nitrogen content, as well as to the deposition temperature.[22,23] There are also indications that they exhibit lower permeability in devices than in sheet films.[20,21] Furthermore, zero magnetostriction and the minimum coercivity do not always occur at the same nitrogen content. Despite these challenges, though, these materials are already adequate (partly because they have such a large margin of moment to spare), and will probably continue to improve as the media coercivity requires it.

4 ADVANCED HEAD ARCHITECTURES

The most serious architectural challenge faced by tape head designers is the operation of many channels in parallel, in very close proximity to one another. Increasing the number of head channels operating in parallel offers increased data rate, but the number cannot be increased without limit, due to tape instability.

For a given span of tracks, the outermost two have an uncertainty in their relative spacing, due to the dimensional instability of the tape. This can be seen in Figure 5, which shows the location of two heads nominally positioned over two tracks of width, W, separated by a distance, L. Tape distortion, has created an offset in the position of track n, by an amount, Δ. A given uncertainty, or track misregistration, sets the span over which heads may operate simultaneously, and be able to insure on-track performance. For example, if the system could tolerate a 5% misregistration ($\Delta = 0.05W$), and the tape distorted by 0.1% ($\Delta = 0.001L$), then L is fixed at $50W$, or 50 tracks.

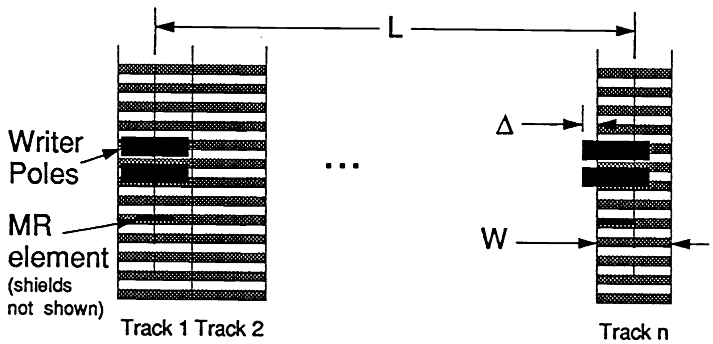

Figure 5: The misregistration, Δ, which results from tape distortion, when two heads attempt to simultaneously read two tracks, separated by a crosstrack distance, L.

The more heads which can fit into this span, L, the larger the number of parallel channels which may be operated. Decreasing this spacing between head channels reduces the area for coil turns, and the head backgap. This suggests that the heads will be less efficient and operating at higher currents (i.e. hotter). It can be seen from Figure 6, which shows a schematic of several adjacent heads on a wafer, that the coils are the geometry limiting feature of the heads.

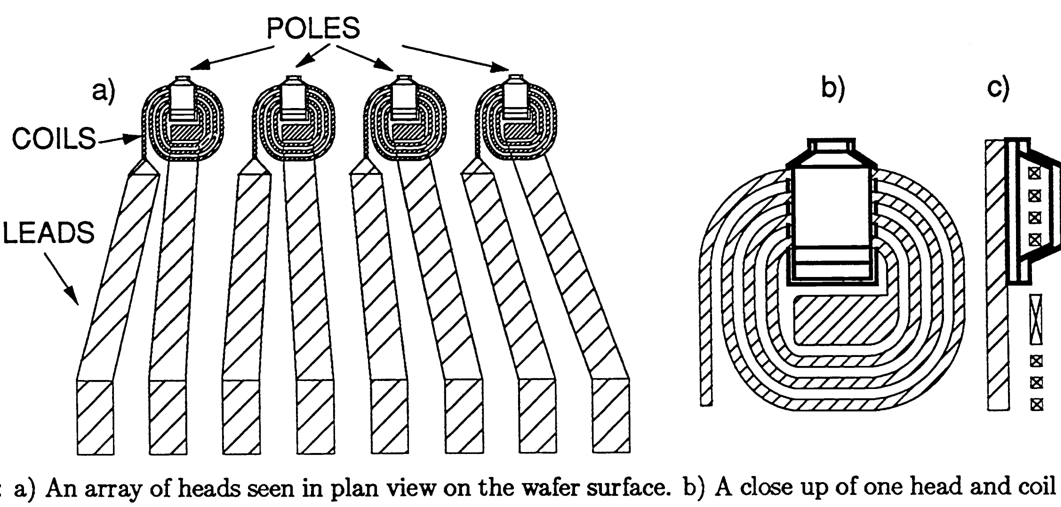

Figure 6: a) An array of heads seen in plan view on the wafer surface. b) A close up of one head and coil assembly in plan view and c) in cross sectional view.

The solution to this problem is to scale down the gap, the pole thicknesses, and the media thickness, in accordance with the head separations. If all dimensions are scaled proportionally, then the head will continue to function the same way, and data rate and tape capacity go up. Consequently, media thicknesses and coil lithography limits set a lower bound on head dimensions, and represent an area in which progress will yield superior head designs (see references for the evaluation of one such design, using thermal and magnetic criteria[24]).

Scaling down the trackwidth allows greater density on a given cartridge (which can be traded for shorter end-to-end time), but puts more stringent requirements on the tape dimensional stability. In the above example, L drops as W drops, meaning that narrower tracks reduce the span available for the head array. Fewer heads mean lower data rate. The magnetics and fabrication challenges associated with very narrow tracks (1-2 μm) are being aggressively addressed by the rigid disk industry,[25] but the systems considerations for multitape array heads will prove just as important as magnetic and processing constraints in determining the optimal trackwidths. Rigid disk head manufacturers do not face this constraint that reducing trackwidth, reduces data rate.

The above assumes that the only source of uncertainty in the track position is due to the dimensional instability in the tape. As a flexible medium tape, it is not only dimensionally unstable (prone to distortion) but it also moves around when it is being transported. Therefore, in order to have the maximum usable span, the newer generations of heads are held on-track by servo motors, much like the rigid disk industry. With the advent of servoed tape systems, (like the QIC 13 Gbyte standard, for example), the tape recording heads must address the numerous issues around servoing, like the servo pattern, the special heads required to write the servo pattern, and to read it back, the location of the servo marks, whether to preformat the tape, or format it in the drive, etc.

As sizes shrink, simplifications of head fabrication and assembly are sought. Much expertise already exists at smaller trackwidths and higher linear densities in the rigid disk recording industry. Of particular advantage would the fabrication a piggyback or shared pole design,[26] which integrates the MR read and the write heads on the same wafer. Although this wafer then becomes more expensive, it does not require the fabrication of two different wafers (a read and a write) or the gluing together of two separately lapped head assemblies, as is currently done. Such a design would reduce the costs associated with complicated assembly, as well as the alignment uncertainties which are added by the assembly process. The feasibility of such a design is heavily dependent on its application. The use of such a head in servoed or read-while-write mode will present significant challenges due to electrical or magnetic feedthru caused by element and lead proximity.

Schemes for reducing electrical coupling between the read and write leads by a sort of stacked lead or stripline approach have been proposed,[27] and in theory could offer a significant reduction in feedthru. Presumably, some similar approach would have to be extended to the off-chip leads and flex circuits as well, to actually reduce the total amount of write signal picked up by the data and servo heads.

5 SUMMARY

Write heads for linear tape recording continue to improve in response to the demands for increasing data rate, decreasing access time, and increasing cartridge capacity. Increases in the saturation induction of pole materials will continue as the amorphous Co alloys, and then the Fe nitrides are brought into wide use. These pole materials will be needed as media coercivity climbs to 2000 Oe (and beyond) which should support greater than 100 KFCI.

The pressure to get the heads in the array as close together will continue, motivating reductions in gap length, and coil pitch, so that the performance can be scaled properly. Tape dimensional stability would offer an improvement here. Fabrication of read and write heads on single wafers may develop, although electrical feedthru while servoing or operating in the read-while-write mode will be a major issue.

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