Design and performance of a magnetic head for a high-density tape drive

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The design of a magnetic head for use in the tape drive portion of the IBM 3480 Magnetic Tape Subsystem required that advances be made in track density and linear recording density while meeting requirements for signal quality, manufacturability, and reliability. The design that was developed to fulfill these needs combines ferrite pole-pieces, magnetoresistive read elements, and planar-deposited write turns. This paper describes the read and write elements of the head and the approach used in the selection of the design parameters.

Introduction

The magnetic-recording heads for half-inch (1.27-cm) tape-drive products have used a nine-track format for more than a decade [1]. The construction of these heads has usually included magnetic foils, which are laminated with a nonmagnetic adhesive material to form the individual track cores. These are then manually wire-wound to form the magnetic circuits for writing data onto tape or for reading the recorded transitions [2]. As linear recording densities and data rates have increased, the thickness of the laminations, the gap lengths, and the head-to-tape separation have all been reduced. There has been little increase in the number of parallel tracks.

In the tape drive for the IBM 3480, the linear recording density has been increased by more than three times and the number of tracks has doubled relative to its predecessor, the 3420. This has required a new chromium-dioxide tape [3] and a reduction in head-tape separation. Both the linear-density increase and the track-density increase lead to reductions in the available magnetic field from which a signal can be derived. The increased number of tracks leads to increased manufacturing costs if conventional nonbatch fabrication techniques are used. Hence, it was necessary to design a head that would be manufacturable in multitrack arrays, be wear-resistant, and have good signal quality. Ferrite inductive heads are a possible solution to linear-density and wear problems. However, the manufacturing cost of an assembled 18-track ferrite head is likely to be very high. Film-processing techniques are most amenable to fabricating multitrack arrays.

It is natural to pursue thin-film technology for this application, because of batch-fabrication characteristics and because it has been the trend for direct access storage devices (DASD) [4]. The inductive thin-film heads used in DASD are unsuitable for tape-drive applications, however, for the following reasons: An excessive number of turns are required to produce an adequate signal at low tape speeds; the exposed metal pole tips are not adequately wear-resistant against tape; the very short throat heights do not allow for any wear to occur; and the thin-film pole tips would saturate before writing could occur on a thick, high-coercivity medium.

The design requirements have been met in the 3480 head by combining magnetoresistive thin-film read elements, planar thin-film write turns, and ferrite pole-pieces. Initial development work was aimed at nine-track enhancements for the 3420 series drives, based on earlier work by Bajorek et al. on magnetoresistive read sensors [5]. Successful prototypes of a nine-track head were fabricated and tested, but they were not suitable for replacement of the conventional laminated heads [6–10]. Subsequent development efforts were aimed at an 18-track version, which ultimately resulted in the new thin-film head for the 3480. The advantages of thin-film batch fabrication, precise control of track dimensions and spacing through photolithography, and the elimination of hand-wound cores were of more potential value for 18-track heads than for the replacement of nine-track heads with their proven record of success. In the following sections we present the features and design considerations of the read and write modules, the thin-film processes, the electrical test parameters necessary to ensure reliable operation of the tape drive, and qualitative descriptions of the head's performance characteristics.

Read module

• *Design constraints and features*

To satisfy reading requirements, it was necessary to design a read head having a high amplitude, high signal-to-noise ratio, high resolution, and low distortion. It was also necessary that the head be manufacturable in multitrack arrays, have adequate life relative to the wear it is subjected to, and have characteristics that remain relatively stable as wear occurs. Additionally, it must not be degraded because of the temperatures encountered in use.

The read element chosen to meet these requirements was the shielded magnetoresistive head [11] with shunt bias [9], shown in cross section in **Figure 1**. The read element includes a nickel–zinc-ferrite substrate on which thin films have been deposited and patterned, and a nickel–zinc-ferrite closure which is held in place with epoxy. The films consist of a magnetoresistive (MR) element of 81% nickel–19% iron, a biasing conductor of titanium, and two spacing layers of aluminum oxide. The MR element is center-tapped and is provided with bias current at the two outside taps, where the signal is sensed differentially.

The ferrite shields that surround the MR element provide the necessary resolution for high-linear-density signals. The MR element amplitude is independent of tape speed and has a much simpler topology than an inductive film head of equivalent amplitude.

The choice of magnetic bias technique was limited to those that were well understood at the time the design was selected. Three could be considered as possible: barber-pole bias [12], soft-film bias [13], and shunt bias. The existence of a simple mathematical model [9] to describe the operation of the shunt-biased MR head has been of great value in determining specification limits and analyzing problems arising in the development and manufacturing processes. This has been extended to consider the case of saturation of the MR element [14].

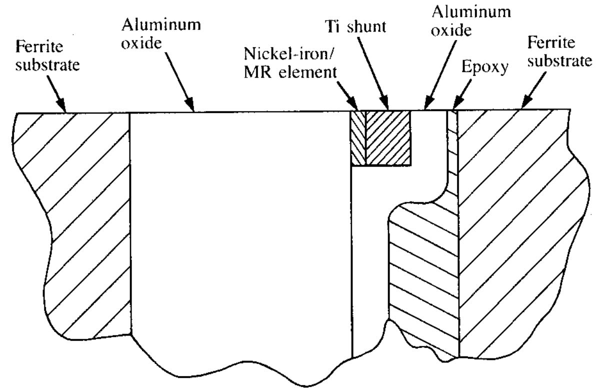

Figure 1

Cross section of the read module.

Second-harmonic distortion, which is a characteristic of MR heads, is reduced by the cancellation effect of the center-tap configuration, combined with a sufficient level of magnetic bias.

The 81% nickel–19% iron has low magnetostriction characteristics and is therefore magnetically well-behaved. Titanium was chosen for the shunt conductor because it does not diffuse into nickel–iron to any appreciable degree at the temperatures used, and its resistivity allows it to be deposited as a relatively thick layer—preferable in order to achieve good thickness control in processing. Furthermore, it has excellent adhesion characteristics and is often introduced in thin-film designs for that reason alone.

The requirement for a magnetically shielded magnetoresistive read head makes it preferable that the substrate material provide the magnetic shielding; otherwise, it becomes necessary to deposit a shield material before forming the MR elements. It is also desirable to have a substrate of high electrical resistance to avoid the occurrence of short circuits. Nickel–zinc-ferrite material meets these requirements. This material can also be polished to a surface suitable for subsequent thin-film depositions and patterning for photolithography. In addition, it is hard and abrasion-resistant, which is a necessity for surfaces at the head-tape interface.

The spacer material must provide a closely controlled separation between the read shields and the MR element. It should also be an electrical insulator and should provide resistance to wear from the magnetic tape. Aluminum oxide

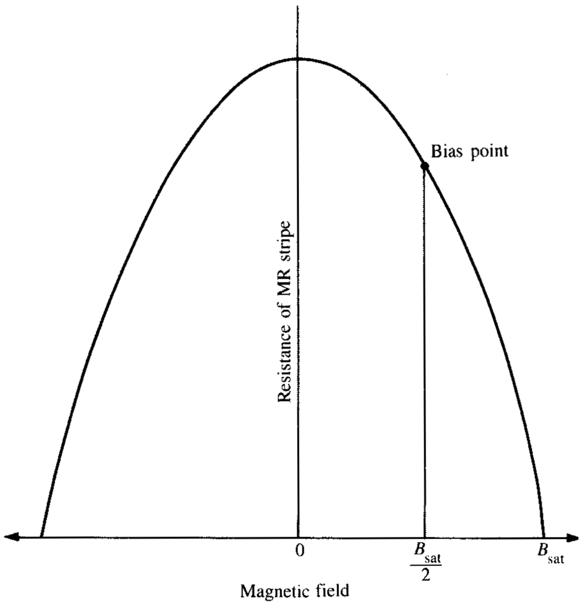

Figure 2

MR stripe response curve.

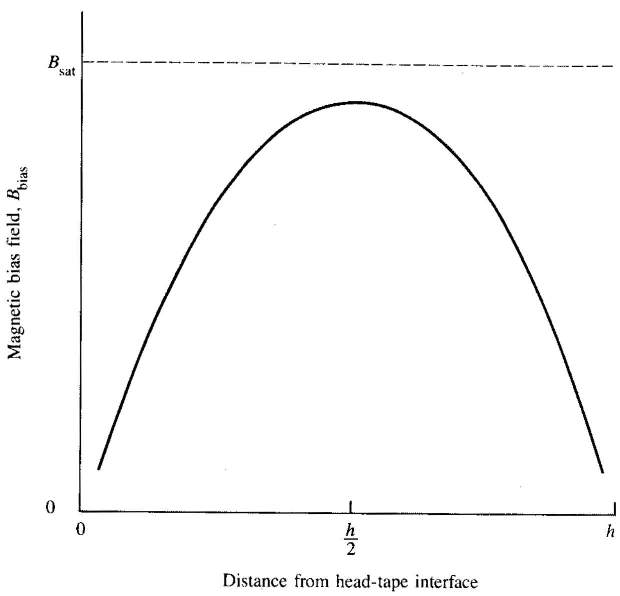

Figure 3

Distribution of bias field across stripe.

was selected because it met all of the criteria listed above and is a fairly good match with ferrite in terms of thermal expansion characteristics.

While the bulk wear resistance of the head is provided by the ferrite substrate and closure, care is needed in the design of the exposed films to ensure that they do not erode. The nickel–iron and titanium films in the 3480 head are very thin and are surrounded by the relatively harder aluminum oxide films. The epoxy-bond line must also be kept thin to minimize erosion and control the gap length. Wear will inevitably occur, and it is necessary that the performance of the device not change radically in the process. The MR element is patterned as a stripe which is positioned perpendicular to the tape. As wear occurs in the shunt-biased MR head, a reduction in stripe height (the stripe dimension perpendicular to the tape) occurs. This is shown to result in a gradual and moderate change, initially an increase, in amplitude.

Heat dissipation in the read element when biased has been found not to be deleterious to the films, the epoxy bond, or the tape.

• *Available signal*

The linear part of the response of the shunt-biased, shielded MR head can be described by the equation

$$e_0(t) = e_{\text{bias}}(\Delta R/R)(t),$$

where

$$(\Delta R/R)(t) = (\Delta\rho/\rho_{\max})[R_{\text{shunt}}/(R_{\text{shunt}} + R_{\text{MR}})] \times (2/h)\int_0^h [B_{\text{bias}}(y)B_{\text{sig}}(y, t)/B_{\text{sat}}^2]dy, \qquad (1)$$

and $e_0(t)$ is the output signal voltage as a function of time, e_{bias} is the dc bias voltage, $(\Delta\rho/\rho_{\max})$ is the magnetoresistivity of the nickel–iron material, R_{shunt} and R_{MR} are the resistances of the shunt and MR films, respectively, h is the MR stripe height, and B_{bias}, B_{sig}, and B_{sat} are the bias, signal, and saturation inductions for the MR film, respectively.

There are many design factors that diminish the realizable signal of a shunt-biased MR head from that which is obtainable from the bulk MR film. If there were no current in the shunt, if B_{bias} were uniform over the stripe height at a value of $1/2\ B_{\text{sat}}$, and if B_{sig} were uniform over the stripe height and were varied in time over the range of 0 to B_{sat} (see **Figure 2**), the peak-to-peak value of $(\Delta\rho/\rho)$ would be $(\Delta\rho/\rho_{\max})$. The factors that reduce signal are as follows:

- A finite shunt resistance is required to carry the current necessary for biasing. The shunt acts as a voltage divider and thus reduces the voltage available at the terminals. This loss is contained in the term in Equation (1).
- The bias field, $B_{\text{bias}}(y)$, is zero at the top and bottom of the stripe and rises to a maximum at the center (see **Figure 3**) [14]. The value at the center may approach or even exceed B_{sat} [15]. Thus, a uniformly ideal bias level cannot be obtained.

- The signal field, $B_{sig}(y, t)$, is a maximum at the head-tape interface. It must be limited by design to a level well short of saturation to control second-harmonic distortion. The signal field leaks into the shields and diminishes to zero at the edge opposite the head-tape interface (see **Figure 4**). As the shield-to-element spacing becomes large with respect to stripe height, one can expect a nearly linear reduction in signal field from front to back of the stripe. At the smaller gap lengths required in practice, this leakage occurs at a faster rate. "Magnetic efficiency" may be defined for this head as the ratio of the average signal field in the head to the maximum signal field, and because of flux leakage the magnetic efficiency of a shielded MR head cannot be greater than 0.5. Magnetic efficiency is qualitatively related to head output but cannot be used in the calculation of output because of the integration over the stripe of the product of B_{bias} and B_{sig} in Equation (1).

The combination of the above effects reduces the realizable resistance change to less than 20% of the maximum magnetoresistance of the nickel–iron material. This is consistent with observations on operating heads.

- *Design considerations*

In the 3480, the maximum recording density is 972 flux changes per millimeter (fcmm) on 18 parallel tracks, and the tape speed is 2.0 meters per second. Read-after-write verification is employed, so that separate read and write functions are required in the head. The tape consists of a pigment containing chromium-dioxide particles on a 25-μm flexible substrate.

Once the basic configuration, materials, and processes had been selected, key dimensions were chosen to achieve a balance between head performance and manufacturability. With regard to the head, the most important analog performance parameters are output amplitude and density response. While amplitude is a function of several head parameters, the rate at which amplitude rolls off with density is primarily controlled by gap length. Thus, the gap length, defined as the distance between the ferrite substrate and closure, as shown in Figure 1, was first chosen to achieve the required density response. Formulas relating the amplitude of the flux entering the element to the gap length can be found in [9, 12, 13]. For the 3480 head, adequate performance and manufacturability are obtained by keeping the gap in a 0.9- to 1.6-μm range.

With the gap length constrained, the thickness of the MR element was chosen to have the correct flux sensitivity. Thin nickel–iron films have reduced magnetoresistive characteristics [16], while thicker films are too insensitive to the high-density signal field used in the 3480 system. In addition, substrate quality and saturation concerns play a great part in determining the thickness of the element. Through theoretical calculation and experimentation, a range of useful thicknesses was derived.

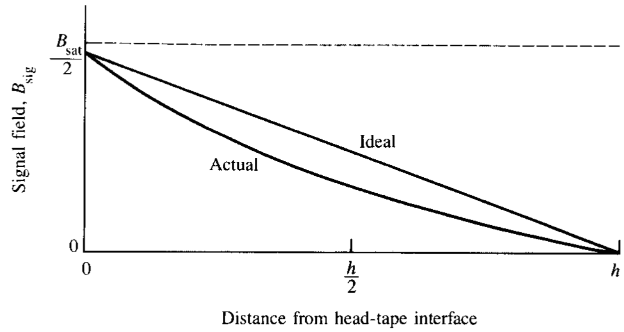

Figure 4

Signal flux in stripe.

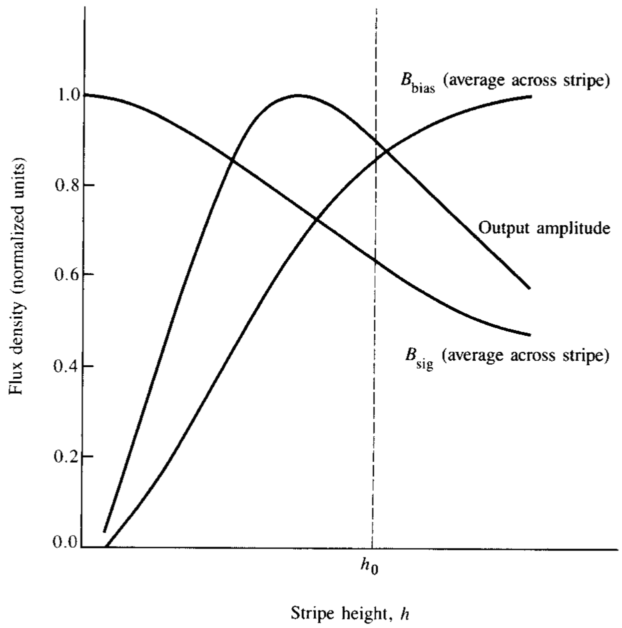

Figure 5

Effect of stripe height on performance.

The remaining design parameters are the stripe height h, the shunt thickness, and the asymmetry of placement of the MR element inside the gap. These parameters interact to determine the shunt loss, the magnetic bias level, the magnetic efficiency, and the wear that the head will tolerate before failure.

The magnetic efficiency is greatest for small values of the stripe height but the magnetic bias is ineffective; for larger stripe heights, the magnetic bias improves but the magnetic efficiency suffers. **Figure 5** shows the interaction of these two effects and the resultant effect on amplitude. It is therefore

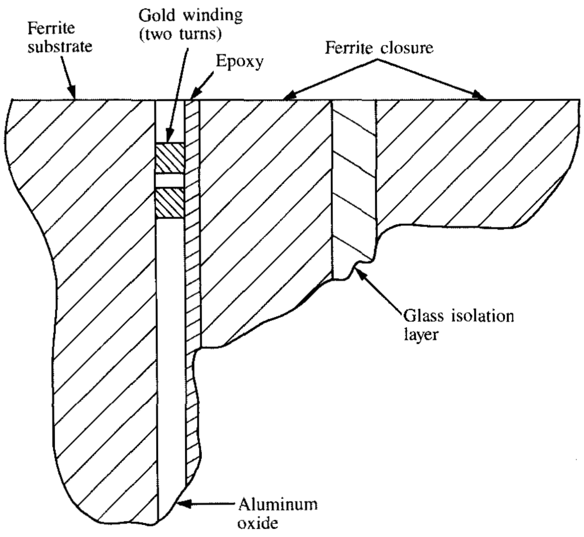

Figure 6

Cross section of the write module.

preferable to choose an initial stripe height h_0 greater than that which maximizes output, so that the head may wear several micrometers before the output falls below a specified fraction of the maximum output.

The shunt thickness and the position of the element in the gap, defined as asymmetry, were chosen to provide adequate bias without unduly sacrificing output. Moving the element off center, by making g_1 less than g_2, improves the magnetic bias [9] but increases the flux leakage and reduces the magnetic efficiency. Care must also be taken to avoid introducing so much asymmetry as to bias the element into saturation [15]. For a given bias current, increasing the shunt thickness also increases the current component in the shunt. This leads to increased bias field, but that must be traded off against the decreased sense current component in the element. Good amplitude performance has been established with the shunt thickness held to about three times that of the MR, and g_2 to about twice the thickness of g_1.

In practice, the dimensions of the head are also limited by process and controllability considerations. Design values are set by an iterative process involving theory and experiment. The effect on performance of a change in any dimension is predicted by the use of transmission-line models, as described in [9, 15].

Write module

Design constraints and features

The write element is required to create reversals of magnetization in the tape in response to modulation of the current supplied to it. The depth of magnetization must be sufficient, and the transitions sufficiently narrow, so that at 972 fcmm a strong signal is produced on read-back. Circuit-design considerations limit the current that can be supplied and the impedance of the write element.

As in the read module, we required that the write module be wear-resistant and that its performance not change as wear occurs. It was to be manufacturable in multitrack arrays; preferably, the manufacturing process was to be similar to that of the read module. Temperature rises caused by joule heating needed to be considered in the design and in the method of writing.

The design of the write module element was similar to that proposed in [10] and is shown in cross section in **Figure 6**. It consists of a nickel–zinc-ferrite substrate on which is deposited a film of gold patterned into a two-turn spiral winding. Aluminum oxide is used as indicated. A nickel–zinc-ferrite closure is held in place with epoxy. The closure includes a glass isolation layer and forms a second magnetic pole-piece. The closure is more complex than in the read module, because it must perform the function of defining the width of the written track. To do this, it is slotted so that for each track there is a pole-piece magnetically isolated from all other tracks.

The operation of the write element is in every way similar to that of a conventional ring head. Given equal gap lengths and pole-tip material properties and a supply of sufficient writing current, the writing qualities should be identical to those of the ring head. The unique features of the design involve the partial substitution of thin-film processes for the machining and assembly processes used in laminated heads or in ferrite heads using discrete wound cores. This has made it possible to produce the write module with manufacturing processes that resemble closely those used to make the read module.

Two turns are used in order to satisfy the combined write drive current limitations and pulse-write inductance requirements. This requires a simpler photolithographic process than do designs with a larger number of turns.

The selection of nickel–zinc ferrite for the substrate and pole-tip material results in a wear-resistant structure which, because of negligible electrical conductivity, does not require any insulating layers. Metal films were rejected because of insufficient wear resistance. Manganese–zinc ferrite, because of its higher conductivity, would have required that insulating layers be added to the film structure.

Analysis and design considerations

Of interest in analyzing the design of the write module are the magnetic efficiency and the magnitude of the gap field. Because of the open back gap and the relatively large recording gap and side fringing paths, a fair approximation of the magnetic efficiency can be obtained by neglecting losses in the ferrite. **Figure 7** is the electrical analog to this model. R_g corresponds to the reluctance of the gap, R_f to the side fringe paths, and R_{bg} to the back gap. These are associated with areas A_g, A_f, and A_{bg} in the following equation. The magnetic efficiency is given by

$$\eta = 1/[1 + R_{bg}(R_g + R_f)/R_g R_f]$$

$$= 1/[1 + (A_g + A_f)/A_{bg}].$$

Once the magnetic efficiency has been estimated and the write current is known, the gap field can be estimated from

$$B_g = \eta(4\pi N I_w/10g),$$

where N is the number of turns, I_w is the write current, and g is the gap length in centimeters.

For the head design used, this field strength is more than half the saturation induction of nickel–zinc ferrite and can be expected to lead to some lengthening of the written transition [17].

• *Reliability of films*

Evaluation of the film layers inside the head with regard to reliability included studies of the adhesion at the film interfaces; possible interdiffusion of nickel–iron and titanium with time, previously thought to be a problem in head degradation; stability with regard to possible film corrosion under various environmental conditions; and the effects of temperature and humidity cycling on performance.

For each, conditions were imposed far in excess of nominal head operating environments, and the results extrapolated to proposed end-of-life requirements. In all cases the head far exceeded established goals.

Performance

• *Signal-quality considerations*

The noise in the system is dominated by three basic components: electrical noise from the circuitry, tape noise, and feedthrough noise at the head. The head noise has three sources: feedthrough between the read and write modules, feedthrough between the read and write cables, and feedthrough between the connectors. The head portion of the feedthrough is handled acceptably by placing a brass shield between the read and write modules.

Feedthrough is only a problem during a read-while-write operation; the rest of the time, signal-to-noise ratio is dominated by the intrinsic noise level of the MR head. An MR sensor gives an inherently clean signal unless the element is saturated or Barkhausen noise is present. The nickel–iron layer of the 3480 head is thick enough that it has neither problem, and the large aspect ratio and substrate quality control the latter.

The impedance of both the write and read heads must be closely controlled for reliable performance. In the case of the read, the balance between the two halves of the center-

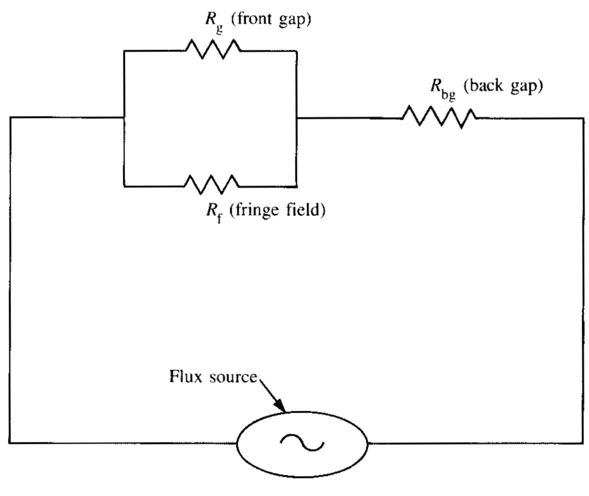

Figure 7

Equivalent-circuit illustration of reluctance paths.

tapped element is the most critical to maintain the benefits of differential sensing. Because the resistance of the read head increases with use, the circuits have been designed to handle a wide range of input resistance. Because of the differential sensing of the read head, good common-mode noise rejection is obtained if the two halves of the head are well matched. The impedance of the write head is important for controlling the shape of the write pulses. The circuitry is designed to produce good write pulses for a specified resistance and inductance. Variations in impedance will change the write pulse, and the ratio of inductance to resistance affects the rise time. Since the circuitry is more sensitive to changes in inductance than resistance, the inductance must be tightly controlled, primarily through gap-length tolerances.

• *Test results*

At a two-meter-per-second tape speed and 972 fcmm density, the 3480 head is capable of 1 to 3 mV of signal amplitude. These amplitude levels produce a signal-to-noise ratio nominally in excess of 24 dB, which permits the excellent reliability characteristics seen in the drive. Moreover, the amplitude remains high over the lifetime of the head because of the wear and shunt-bias characteristics of the MR element. The head eventually becomes no longer useful at a point when the increasing head impedance begins to degrade the channel performance by contributing excess noise to the system.

With the double-pulse write scheme, the dynamic range characteristics of the MR head are also quite favorable: Using a standard measure where the dynamic range is defined as the ratio of the 486-fcmm and 972-fcmm signal amplitudes, typical head values are in the 2.2 to 2.7 range. With this density response, the requirements for channel equalization are eased and circuit costs reduced.

The write head is designed to operate at 220 mA of current, optimized for the 972-fcmm density written on tape with a 525-oersted coercivity. In addition, the semi-infinite pole-piece (ferrite) and relatively thick recording layer combine to produce a very flat write-saturation characteristic on either side of the 220-mA nominal current. This demonstrates the forgiving nature of the planar thin-film design, and its ease of manufacture.

Summary

The read/write head for the IBM 3480 Magnetic Tape Subsystem has been designed as a combination of ferrite and thin-film technologies to satisfy the demands of a high-density, high-reliability tape storage device. Associated design considerations and trade-offs have been described. Simple theoretical analyses were performed for the read and write processes and related to the design.

Acknowledgments

The 3480 tape head is the result of effort by many individuals in various IBM locations. It is not possible to recognize individually each of the persons who contributed to the development of the thin-film processes for the head. However, the authors wish to acknowledge these contributors and thank them for their efforts.

References

1. For example, see J. P. Harris, W. B. Phillips, J. F. Wells, and W. D. Winger, "Innovations in the Design of Magnetic Tape Subsystems," *IBM J. Res. Develop.* **25,** 691–699 (1981).
2. V. R. Witt and R. C. Bradford, "Magnetic Transducer," U.S. Patent 2,922,231, 1960.
3. R. Bradshaw, B. Bhushan, C. Kalthoff, and M. Warne, "Chemical and Mechanical Performance of Flexible Magnetic Tape Containing Chromium Dioxide," *IBM J. Res. Develop.* **30,** 203–216 (1986).
4. Robert E. Jones, Jr., "IBM 3370 Film Head Design and Fabrication," *IBM Disk Storage Technology*, pp. 6–9, 1980; Order No. 26-1665, available through IBM branch offices.
5. C. H. Bajorek, C. Coker, L. T. Romankiw, and D. A. Thompson, "Hand-Held Magnetoresistive Transducer," *IBM J. Res. Develop.* **18,** 541–546 (1974).
6. G. W. Brock, F. B. Shelledy, and A. B. Wills, "Process for Making a Read-While-Write Tape Head and the Product Made Thereby," U.S. Patent 4,044,392, 1975.
7. G. W. Brock and F. B. Shelledy, "Methods for Manufacturing and Using an Internally Biased Magnetoresistive Magnetic Transducer," U.S. Patent 3,967,368, 1975.
8. G. W. Brock, F. B. Shelledy, S. H. Smith, and R. M. Thornley, "Shielded Magnetoresistive Magnetic Transducer," U.S. Patent 3,940,797, 1975.
9. F. B. Shelledy and G. W. Brock, "A Linear Self-Biased Magneto Resistive Head," *IEEE Trans. Magnetics* **MAG-11,** 1206–1208 (1975).
10. G. W. Brock and F. B. Shelledy, "Batched Fabricated Heads from an Operational Standpoint," *IEEE Trans. Magnetics* **MAG-11,** 1218–1220 (1975).
11. R. I. Potter, "Digital Magnetic Recording Theory," *IEEE Trans. Magnetics* **MAG-10,** 502–508 (1974).
12. K. E. Kuijk, W. J. van Gestel, and F. W. Gorter, "The Barber Pole, a Linear Magnetoresistive Head," *IEEE Trans. Magnetics* **MAG-11,** 1215–1217 (1975).
13. T. J. Beaulieu and D. A. Nepela, "Induced Bias Magnetoresistive Read Transducer," U.S. Patent 3,864,751, 1975.
14. D. A. Thompson, "Magnetoresistive Heads in High-Density Magnetic Recording," *AIP Conference Proceedings, 20th Annual Conference on Magnetism and Magnetic Materials*, 1975, p. 528.
15. D. J. O'Connor, F. B. Shelledy, and D. E. Heim, "Mathematical Model of a Magnetoresistive Read Head for a Magnetic Tape Drive," *IEEE Trans. Magnetics* **MAG-21,** 1560–1562 (1985).
16. S. Krongelb, "The Preparation and Properties of Magnetoresistive Permalloy Films," *J. Electron. Mater.* **2,** 227–238 (1973).
17. H. N. Bertram and C. W. Steele, "Pole Tip Saturation in Magnetic Recording Heads," *IEEE Trans. Magnetics* **MAG-12,** 702–706 (1976).

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