ADVANCEMENTS IN RESEARCH OF MAGNETIC RECORDING

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ABSTRACT - This paper reviews some of the advancements in the research and development of magnetic recording media and heads for applications in high-density information storage systems. In particular, advancements in the understanding of the fundamental mechanisms in perpendicular and longitudinal recording processes, media, and heads are discussed. Advancements in the designs and materials of media and heads, calculations of recording performance, and new measurement techniques are reviewed. It is concluded that the development of magnetic recording technology is accelerating and needs rapid advancements in the research of media, heads, and the head-media interface. Interactions between university and industry can assist in advancing magnetic recording research to achieve the ultra-high areal densities and reliability required for future information storage systems.

INTRODUCTION

Because the principles of magnetic recording were invented a century ago [1,2] and the advancements in the research and development of magnetic recording media and heads were made mostly by industry during the past 40 years, a myth still exists today that magnetic recording is so mature that there must be few research challenges left. On the contrary, the research and development of magnetic recording as a high-density information storage technology is exciting and is growing as rapidly as microelectronics memory technology did over the past 30 years. Because of the similar development of submicron-size devices in microelectronics, the magnetic recording field should be called "Micromagnetics".

The purpose of this paper is to review some of the advancements in the research and development of magnetic recording media and heads for applications in high-density information storage systems, discuss advancements in the understanding of the fundamental mechanisms in perpendicular and longitudinal recording processes, media, and heads, evaluate new materials for media and heads, discuss models of magnetic recording at ultra-high densities, and review new measurement techniques.

FUNDAMENTALS OF MAGNETIC RECORDING

The 1951 classical paper by Wallace [3] on the ring head reproduction of a pure sinusoidal recording in electroplated thin film media presented measurements and a theory of an exponential loss of signal due to a separation between the media and head. Daniel and Axon [4] reported essentially the same result earlier in 1950. The simple Wallace theory assumed that a longitudinal or perpendicular magnetization mode was uniform through the thickness of the media and predicted identical signals for both modes except for a 90 degree phase shift. The calculation assumed a zero-gap ring head with finite permeability. Even though the Wallace theory was a very significant contribution at the time, its assumptions are not valid today for comparable gaps, thicknesses, and separations, and media and heads with finite anisotropic permeability.

The theoretical work by Westmijze [5] in 1953 on the reproduction of either pure sinusoidal longitudinal or perpendicular uniform remanent magnetizations assumed media to have constant linear permeability and infinite permeability for a ring head with a zero-gap. The calculations predicted no difference in the magnitude of the reproduced output for both modes. However,

the finite permeability of the media does account for some of the head-media magnetic interactions which alter the distribution of the magnetic flux density inside and outside the media and the amplitude of the head output at different separations. The Westmijze theory is not applicable today for recording systems having comparable gaps, thicknesses, and separations, and finite anisotropic permeabilities.

The Wallace or Westmijze theories of linear reproduction of pure sinusoidal recordings do not take into account any nonlinear effects of the writing process which can produce nonuniform magnetization distributions along and through a media. Neglecting demagnetizing fields and using the longitudinal fields of a zero-gap ring head and the nonlinear field-dependence of the longitudinal remanent magnetization of the media, Teer [6] determined the shape of the profile of the remanent magnetization of an isolated transition written by a step function in 1961. He obtained this result using a graphical technique and the principle of reciprocity [5]. Even this simple model showed that the reproduced pulse shape written by a step function is quite asymmetrical due to the nonlinear dependence of the remanent magnetization of the media on field. The principle of reciprocity can be used to obtain the shape of the reproduced output for any head if the spatial distribution of both of the field components of head and the remanent magnetization are known. The usual procedure is to use the 1954 Karlqvist [6] approximation for the field components of a finite gap ring head. If the profile of the longitudinal remanent magnetization is assumed to be an ideal step function, the shape of the output is identical to the longitudinal head field. The Karlqvist approximation of a ring head is acceptable if the media to head separation is greater than 1/10 of the gap length. Otherwise, at very small separations, the longitudinal field of real ring heads near the gap edge exhibits a sharp maximum which can be altered significantly by the permeability of the media. In 1961, Fan [7] calculated that the exact field components of an ideal finite gap ring head gives a maximum in the longitudinal field near the gap edges.

A dramatic demonstration of the vector nature and nonuniform distribution of the remanent magnetization in recorded media was given in 1963 by Tjaden and Leyten [9] who recorded on a longitudinally-orientated magnetic media 5 cm thick using a 5000:1 large-scale model of a ring head with a gap of 2 cm. After a step function recording, the vector magnetization exhibited a large perpendicular component through the media near the center of the transition. This single experiment constituted a fundamental advancement in the understanding of the behavior of the magnetic recording process by showing that both the longitudinal and perpendicular components of the media magnetization participate in the recording process and neither should be neglected. In 1968, Iwasaki and Suzuki [10] presented self-consistent iterative calculations taking into account demagnetization fields and the nonlinear field-dependence of the vector magnetization in stand-still magnetic recording. Their results for the longitudinal and perpendicular components of the magnetization confirmed the Tjaden's large-scale recording experiments.

In 1975, Iwasaki and Takemura [11] reported another confirmation of the vector nature and nonuniform distribution of the remanent magnetization in actual standard recording media by showing Bitter patterns of cross sections of recorded media. They showed that the formation of a circular mode of magnetization within the media corresponds to the null in the output as a function of write current and they were able to decouple the circular mode into a perpendicular mode by applying a strong magnetic field nearly normal to the media. This result constituted an advancement in the research of magnetic recording because it suggested that the perpendicular mode, because of reduced self-demagnetization, should be considered for high-density recording. In 1977, Iwasaki and Nakamura [12] presented measurements confirming the use of the perpendicular magnetic recording mode at high-densities in new RF-sputtered CoCr films reported in 1978 by Iwasaki and Ouchi [13] to possess a net perpendicular magnetic anisotropy. These advancements marked the beginning of a new era in magnetic recording technology.

MAGNETIC RECORDING MEDIA

The original idea of magnetic recording media has remained unchanged since its invention. The first practical magnetic recording machine, built by in 1898 by Poulsen [14], used carbon steel wire as the recording media. The recording properties of wire media were improved by using stainless steel wire which was drawn and annealed to produce an oriented array of precipitated fine isolated single domain ferrite particles. Wire recorders were used until the development of tapes coated with fine magnetic single domain particles of gamma iron oxide dispersed and oriented in a plastic binder by Baudisch [15] in 1933. Since this beginning, there have been many advancements in understanding fundamental mechanisms of magnetic recording which resulted in significant improvements in the magnetic properties, structures, and the quality of magnetic media available today.

All of the advancements of particulate magnetic recording media been focused to make thinner, smoother, and denser tapes or disks with higher coercivity and lower noise. Fine particles have been developed which have either a large shape anisotropy as in chrome dioxide [16] and iron metal [17] or large crystalline anisotropy as in Co-substituted [18], Co-impregnated gamma iron oxide [19], and barium ferrite [20]. Most of the problems which have limited the use of particulate media for higher recording density applications, such as low coercivity, low squareness and coercivity squareness, low flux density, large switching field distribution, dispersion, roughness, and corrosion have been solved today. For example, after about 30 years of development, iron metal particle tape with a 1500 oe. coercivity is used commercially for DAT and 8 mm video. Even the problem of limited minimum thickness has been solved by using partial penetration recording. However, the key issue is still the media signal-to-noise ratio (SNR) which is directly proportional to $\frac{1}{3}$ the number of magnetic particles per cm^2 [21]. The SNR has been increased from 10^{14} for gamma iron oxide to 10^{16} for iron particles. Advancements of particle density to 10^{18} should be possible with thin film media.

The accelerating world-wide demand for significantly higher-density information storage media at lower cost/megabyte has driven the magnetic recording industry to develop thin film media for analog tape storage and data disk storage systems. The main reasons for the transformation from particulate to thin film media are that it can be made thinner with unity packing fraction to give higher output at higher densities. Thin film rigid disk media captured about 63% of the market in 1988 while oxide disk media had only 37%, and thin film media is expected to capture about 81% in 1991 [22]. However, there are still a number of issues that make the development of thin film media difficult such as control of process variables to obtain high coercivity and low noise simultaneously, uniformity, defects, stiction, friction, durability, corrosion, reliability, manufacturability, and cost. Some of the advancements in the research of magnetic properties, recording output and noise, and micromagnetics of longitudinal and perpendicular plated, evaporated, and sputtered thin film media are reviewed.

Electrochemical deposition of magnetic thin films for magnetic recording began with Zapponi [23] in 1952 but the coercivity was only 280 oe. Addition of phosphorus to the bath by Bonn and Wendell [24] in 1953 increased the maximum coercivity to 1750 oe probably because phosphorus segregation at grain boundaries caused the grains to behave magnetically like single domains. The technique of autocatalytic chemical deposition was described in 1946 by Brenner and Ridell [25] to improve thickness uniformity. This technique was used in 1962 by Fisher and Chilton [26] and Judge et al [27] in 1965 to deposit thin films of CoP on PET plastic substrates. Bate et al [28] investigated electroless CoP films and found some films with a HCP c-axes oriented perpendicular to film plane to have a coercivity of 300 oe., whereas films with c-axes randomly oriented in the film plane had coercivities of about 1000 oe. In 1982, the development of a 8" diameter CoP plated disk, 300 Å thick and 300 oe. coercivity, was reported by Suganuma et al [29] to have a D_{50} of 74 Kbp/ in at 0.12 μm flying height using a 0.2 μm gap MnZn head. In 1988,

Kazuetsu et al [30] reported on the magnetic properties and noise of electroless-plated CoNiP disks. They found that the media noise correlates with the rotational hysteresis loss integral ratio indicating that high modulation noise may be due to domain wall motion while high modulation noise may be due to rotational processes. High-coercivity CoMoMnP thin films with perpendicular anisotropy have been made by Osaka et al [31] using electroless plating.

The above review of the advancements in the research and development of plated thin film media shows that impressive progress over the past 25 years. However, since some problems still exist with process control, trapped impurities, defects, durability, and yields, the magnetic recording industry has had to consider alternatives such as evaporated and sputtered thin film media. As expected, the advancement of these media follows the approach used for plated media.

Research and development of evaporated thin film media has continued in spite of difficulties such as defects, corrosion and mechanical durability. Early work on longitudinal metal-evaporated tape (MET) was reported by Sugaya [32]. This media is fabricated by evaporating on a thin base film of polyester at a large angle of incidence (70 deg.) from the film normal and a very high deposition rate (1 $\mu\text{m}/\text{sec}$). The origin of the high magnetic coercivity (1500 oe.) is due to the shape anisotropy of the microstructure caused by atomic shadowing. According to Shinohara et al [33], the durability of MET has been improved enough by evaporating in an oxygen atmosphere to survive 1 hr still frame. Perpendicular MET has been developed by Sugita et al [34] and Kitakami et al [35] by evaporating thin films of CoCr on thin layers of Ti (200 Å) to enhance the basic perpendicular anisotropy. Sugita et al [34] reported a CN ratio of 45 dB at 130 Kfrpi using ferrite head with a 5 μm track width. Honda et al [36] reported oxidation of the surface (120 Å) of evaporated CoCr films reduced the friction. These advancements demonstrate that an extremely high areal density of 1 bit/ μm^2 is quite feasible so that a small durable digital VTR for home use may be possible in the near future.

So many advancements have been made in the research and development of sputtered magnetic thin films that half of the small disk drives in 1988 use sputtered disks (37%) instead of plated (26%) or oxide (37%) disks [22]. By 1991, sputtered thin film media will serve 60% of the PC drive market. The advantage of sputtering over other thin film deposition techniques is the capability of depositing very thin films over a wide range of metallic alloys and insulating compounds with excellent reproducibility and adhesion. Sputtered thin film media can be classified by the recording mode as either longitudinal or perpendicular and by the state of the material as oxide or metallic alloy used.

In 1974, Comstock et al [37] and Inagaki et al [38] in 1976 succeeded in obtaining thin films of gamma ferric oxide by sputtering on NiP/Al disks. These were the first attempts to form a continuous thin film magnetic oxide material which had high coercivity, high remanent magnetization, and was very corrosion and wear resistant. After many improvements in the preparation techniques, Yoshii et al [39] reviewed various fabrication processes and recording characteristics of gamma ferric oxide thin film media by reactive RF sputtering and successive heat treatments. Films with a thickness of 0.12 μm , a coercivity of 1000 oe., a coercivity squareness of 0.84, and a remanent flux density of 3000 G., exhibited a -6 dB density D_{50} of 2600 fc/mm and a signal-to-noise ratio (SNR) of 35 dB at 1000 fc/mm using a MnZn ferrite head with a gap of 0.15 μm , a track width of 10 μm , and a fly height of 0.1 μm . These advancements were significant because they demonstrated for an attractive alternative to standard coated oxide particulate media and even to plated thin film media. However, problems with cost and mass production may prevent sputtered oxide from being competitive.

Sputtered thin films of metal alloys have become successful alternatives to sputtered oxide and plated media for high-density longitudinal and perpendicular recording media because of the availability of higher coercivity, higher output, lower noise, and better corrosion resistance. Sputtered thin film metal alloy media can

be classified with respect to deposition on either bare substrates or substrates which are covered with a thin film underlayer. In the former case, the high coercivity is obtained by growing isolated grains which can evolve into a columnar structure. In the latter case, the high coercivity occurs because of an epitaxial growth on the microstructure of the underlying film. In both cases, the coercivity of the films can be enhanced and the media noise can be reduced by forming smaller grains and inducing segregation thermally.

A perpendicular CoCr film RF sputtered on a polyester substrate was reported by Iwasaki and Ouchi [13] in 1978 to possess columnar structure and a perpendicular anisotropy. Iwasaki and Nakamura [12] reported that after writing on a 1 μm thick CoCr film with a single pole type head with a 3.5 μm thick main pole, they could recover signal near 50 Kfrpi using a ring head with a gap of 1 μm . A longitudinal CoNiPt film was RF sputtered directly on a bare NiP/Al disk substrate in 1983 by Yanagisawa et al [40]. They found that even a 300 $\text{\AA}$ thick CoNiPt thin film is extremely corrosion resistant, has a coercivity of 893 oe. and coercivity squareness of 0.97, a high remanent flux density of 10.5 KG, and has a high D_{50} of 51 Kfrpi when a using a MnZn ferrite head with a 0.46 μm gp, 32.3 μm track width, and a 0.12 μm flying height. However, in 1983, Baugh et al [41] reported a large increase in media noise occurs with increasing recording density for longitudinal films of Co, CoNi, and CoRe sputtered on NiP/Al disks.

In 1979, Iwasaki et al [42] reported using RF sputtering to deposit perpendicular CoCr on an underlayer of NiFe. They recorded on a 0.5/0.5 μm thick film of CoCr/NiFe with a 1 μm thick single-pole type head and they could recover signal near 100 kfrpi using a ring head with a 0.67 effective gap. In 1987, Yamamoto et al [43] reported writing and reading the ultra-high density of 680 Kfrpi with a single pole head. Even though this was a laboratory result, it is still an amazing advancement in the research and development of sputtered perpendicular thin film media that demonstrates the incredible potential of magnetic recording technology.

The idea for using a Cr underlayer to enhance the coercivity of evaporated longitudinal Co films was reported by Lazzari et al [44]. The epitaxial growth of the Co film on the Cr was explained by Daval and Randet [45] in 1970. In 1979, a Co thin film was RF sputtered on a thin film Cr underlayer which had been deposited on NiP/Al disk substrates by Maloney [46] who found the coercivity of longitudinal Co film to increase up to 1000 oe. for Cr thickness of 1 μm and to decrease rapidly with Co thickness. Using DC magnetron sputtering, Yamada et al [47] reported obtaining a coercivity of 1100 oe. for CoNiCr/Cr films in 1985, and in 1986, Fisher et al [48] reported a 1400 oe. coercivity for CoCrTa films sputtered on Cr-coated NiP/Al disks. Both longitudinal films gave excellent recording performance at high densities. In 1988, Christner et al [49] reported on low noise longitudinal CoCrM/Cr 500 $\text{\AA}$ film media in which the noise is nearly independent of density up to 80 Kfrpi, the media SNR was greater than 35 dB up to 30 Kfrpi, the D_{70} was greater than 20 Kfrpi for a coercivity of 1300 oe. In 1988, Shiroishi et al [50] reported on the corrosion resistance and noise of longitudinal thin films of CoCrM/Cr where M was Pt, Ta, and Zr. Essentially no corrosion was found for CoNiZr/Cr and the lowest noise film was the CoCrTa/Cr. They also found that the media noise was smallest when the total anisotropy constant was also smallest suggesting that the perpendicular anisotropy lowers the transition noise. In 1989, Tani et al [51] reported that the coercivity of CoNiCr/CrGd/NiP/Al film media can be made greater than 2000 oe. by using temperature and bias. In 1989, Shiroishi et al [52] reported obtaining low modulation and high SNR by using two optimized Cr layers. Hsu et al [53] will report at PMRC on an effective epitaxial thickness of only 400 $\text{\AA}$ for longitudinal RF sputtered CoCrTa thin films deposited on Cr above which the perpendicular orientation of the films starts to become discernible.

These remarkable advancements in the past decade on the research and development of longitudinal sputtered thin film media are impressive compared to the development time for metal particles and plated media.

The design of single-sided ring heads evolved from the original double-sided perpendicular head used by Poulsen [2] in which the media passed through the gap of an electromagnet. The advancement and development of the ring head has not changed until recently. However, materials have improved from metal laminations to ferrite and fabrication techniques such as glass bonding have improved efficiency, durability, and expanded applications. The early work of Westmijze [5], Teer [6], Karlqvist [7], Fan [8], Tjaden and Leyten [9], and Iwasaki and Takemura [11] clearly explained how the fields of a ring head interact with a longitudinal media. In 1977, Iwasaki and Nakamura [12] discussed how a single-pole type head interacts with a perpendicular media. In 1975, Romankiw and Simon [54] advanced head technology by introducing batch fabrication of thin film inductive heads. This work resulted in the invention of the IBM 3370 film head by Jones [55] and Nystrum around 1980. The IBM thin film head involves electroplating of the Permalloy core and many microelectronic processing, plating, sputtering, and precision mechanical steps. The sputtered thin film head design of Hanazono et al [56] avoids the limitation of magnetic materials than cannot be plated. In 1979, Szczech [57] reported for the first time simple analytical expressions for the field components of a large-scale thin film head which an engineer can use easily. Iwasaki et al [58] demonstrated that sharp narrow (6.5 μm wide) tracks could be recorded and read a double layer CoCr/NiFe perpendicular magnetic recording media. In 1987, Lambert et al [59] reported recording and reading with etched 0.5 μm tracks on longitudinal magnetic recording media. A single-sided floppy disk head of the double-gap design was introduced by Hokkyo et al [60] in 1984. In 1984, Yamada et al [61] developed a new high flux density amorphous CoZr thin film material for film heads. In 1977, Hunt [62] introduced a flux sensing magnetoresistive head (MR) which is still under development. In 1988, Shinohara et al [63] described the characteristics of the metal-in-gap head which is now exciting and revolutionizing the tape and disk recording industry.

In 1974, Dressler and Judy [64] reported on a study of digitally recorded transitions in continuous longitudinal CoCr thin films using Lorentz transmission electron microscopy (LTEM) as did Daval and Randet [45] in 1970. The motivation for this research was to try to understand the fundamental processes and limitations of recording on high-coercivity thin films for high density applications. They found that the transition regions were defined by cross-walls in a saw-tooth-like zig-zag domain structure which was quite different from the continuous transitions assumed in the recording theories at the time. The amplitude of the zig-zag domain structure decreased with increasing coercivity. In 1981, Chen advanced the understanding of the effects of micromagnetic properties of high-coercivity metallic thin films on recording density and concluded that 25 Kfrpi was an upper limit. In 1984, Tong et al [66] reported many details of the micromagnetics of recorded tracks written by a head flying 6 to 10 microinches above the disk coated with a 450-490 oe. FeCoCr thin film. The recorded patterns were studied using ferrofluid Bitter technique and LTEM. They also observed a zig-zag sawtooth domain structure in the isolated transitions which was related to bit shift, readback asymmetry, and overwrite. In 1985, Belk et al [67] presented a model of zig-zag transitions and measurements of the noise of in high coercivity thin film media as a function of recording density. They showed that the noise increased significantly in standard longitudinal plated CoP and CoNiP and sputtered CoRe thin film media, was constant for particulate media, and even decreased for CoCr perpendicular media. Several more studies of the micromagnetics and noise of thin film media [68-74] have advanced the understanding of the relation between microstructures, micromagnetics, and noise. In 1988, Chen and Yamashita [75] concluded that the hysteretic properties of Co based metallic thin film media are affected strongly by the magnetostatic and exchange interactions between the particles. They also found that noise and bit shift can be decreased appreciably by reducing the exchange coupling between crystallites.

MODELING AND MEASUREMENT TECHNIQUES

CONCLUSIONS

Advancements in the research and development of magnetic recording storage technologies have always seemed to depend upon guidance from the latest models of the process being studied and from use of the latest measurements techniques available. The situation has not changed much today. In 1989, Tagawa and Nakamura [76] reported on further enhancements of their model of the hysteretic incoherent magnetization curling processes involved in the recording of perpendicular and longitudinal magnetic recording media. They have now included the finite element method (FEM) in their model to take into account the nonlinear magnetic interactions between the head and media. The most important contribution of their model is that it includes head-media interactions which are important at ultra-high recording densities. In 1983, Yoshida et al [77] reported on the technique of using electron holography to observe/recorded magnetization distributions. In 1988, McFadyen [78] showed how the differential-phase contrast technique of Lorentz microscopy can be implemented in conventional scanning transmission electron microscopes. However, this method is limited to thin (1000 Å) samples which are transparent to electrons. However, Mitsuoka et al [79] successfully used the technique of spin-polarized scanning electron microscopy to study the magnetic domains in thin film heads. This technique has a very large depth of field so it is independent of surface roughness. In 1989, Koeppe and Kryder [80] reported enhancing their small step (0.2 µm) scanning magneto-optical Kerr microscope to observe the dynamic magnetics of MIG heads and they were able to detect the presence of a dead magnetic layer between the metal and the ferrite. In 1989, Rugar et al [81] described their use of magnetic force microscopy for imaging magnetic domains with 500 Å resolution. In 1987, Yanagisawa et al [82] described a thin film microhardness tester with a 50 Å sensitivity. In 1989, Mate et al [83] reported using an atomic force microscope to determine the surface morphology of carbon films with a resolution of 20 Å laterally and 2 Å high. The techniques available today are truly incredible!

Some of the advancements in the research and development of magnetic recording media and heads for applications in high-density information storage systems have been reviewed. In particular, an attempt was made to identify the key advancements in understanding the fundamental mechanisms in perpendicular and longitudinal recording processes, media, and heads, evaluate new materials and designs for media and heads, discuss models of magnetic recording at ultra-high densities, and review new high-resolution measurement techniques. Probably one of the most important lessons to learn from this review is that magnetic recording is really not so old. It appears that repeating old research with improved models and techniques is useful. We have seen many times how old ideas about recording can be discouraging until someone has the courage to introduce new ideas which may lead to better understanding and further advancements in the technology. It will probably not be understood for many years what will be considered the greatest benefit derived from the rebirth of perpendicular magnetic recording 15 years ago in an industry that did not seem to be interested in understanding fundamental ideas about recording. Besides promising unbelievable storage densities in the future, perpendicular recording may have effectively helped ignite a tired industry into a focused effort to extend the life of longitudinal recording systems. This review has shown that the limits of longitudinal recording are far from being attained. The challenge now is to advance the state of the art of magnetic thin film inductive, magnetoresistive, MIG head, and new heads in an integrated optimization with the best available particulate and thin film media.

It is concluded that the development of magnetic recording technology is definitely accelerating and needs rapid advancements in the research of media, heads, and the head-media interface. Interactions between university and industry can assist in advancing magnetic recording research to help in achieving the reliability required for the ultra-high areal densities expected for future information storage systems.

REFERENCES

1. O. Smith, "Some Possible Forms of Phonograph", *Elec. World*, vol. 12, pp. 116-7, 1888.
2. V. Poulsen, "Das Telegraphphone", *Ann. Phys.*, vol. 3, pp. 754-60, Nov. 1900.
3. R.L. Wallace, Jr., "The Reproduction of Magnetically Recorded Signals", *Bell Sys. Tech. J.*, vol. 30, pp. 1146-73, 1951.
4. E.D. Daniel and P.E. Axon, "Accidental Printing in Magnetic Recording", *B.B.C. Quart.* vol. V, pp. 7-22, Winter 1950.
5. W.K. Westmijze, "Studies on Magnetic Recording", *Philips Res. Repts.*, vol. 8, pp. 148-157, 161-183, 245-269, 343-366, 1953.
6. K. Teer, "Investigations of the Magnetic Recording Process with Step Functions", *Philips Res. Repts.*, vol. 16, p. 469-91, 1961.
7. O. Karlqvist, "Calculation of Magnetic Field in the Ferromagnetic Layer of a Magnetic Drum", *Trans. Roy. Inst. Tech. Stockholm*, vol. 86, pp. 1-28, 1954.
8. G.J. Fan, "A Study of the Playback Process of a Magnetic Ring Head", *IBM J. Res. Dev.*, vol. 5, pp. 321-5, Oct. 1961.
9. D.L.A. Tjaden and J. Leyten, "A 5000:1 Scale Model of the Magnetic Recording Process", *Philips Res. Repts.*, vol. 25, pp. 319-29, 1963-1964.
10. S. Iwasaki and T. Suzuki, "Dynamical Interpretation of Magnetic Recording Process", *IEEE Trans. Magn.*, vol. MAG-4, pp. 260-72, Sept. 1968.
11. S. Iwasaki and K. Takemura, "An Analysis for the Circular Mode of Magnetization in Short Wavelength Recording", *IEEE Trans. Magn.*, vol. MAG-11, pp. 1173-75, 1975.
12. S. Iwasaki and Y. Nakamura, "An Analysis for the Magnetization Mode for High Density Magnetic Recording", *IEEE Trans. Magn.*, vol. MAG-13, pp. 1272-9, 1977.
13. S. Iwasaki and K. Ouchi, "CoCr Recording Films with Perpendicular Magnetic Anisotropy", *IEEE Trans. Magn.*, vol. MAG-14, pp. 849-51, Sept. 1978.
14. V. Poulsen, "Method of Recording and Reproducing Sounds or Signals", U.S. Patent: 661-619-1900, 1898.
15. O. Baudisch, "Gamma Ferric Oxide Hydrate and Method of Making Same", U.S. Patent: 1-804-749, Jan. 2, 1933.
16. T.J. Swoboda, P. Arthur, N.L. Cox, J.N. Ingraham, A.L. Oppegard, and M.S. Sadler, "Synthesis and Properties of Ferromagnetic CrO₂", *J. Appl. Phys.*, v. 32, 374-75, 1961.
17. K. Nagai, S. Iwasaki, and K. Yokoyama, *J. I.E.E.*, Japan, vol. 77, pp. 688-94, 1957.
18. S. Nobuoka, T. Ando, and F. Hayama, "Method of Preparing Magnetic Recorder Powder", U.S. Patent: 3-081-264, Mar. 12, 1963.
19. Y. Imaoka, S. Umeki, Y. Kubota, and Y. Yokuoka, "Characteristics of Cobalt-Absorbed Iron Oxide Tapes", *IEEE Trans. Magn.*, vol. MAG-14, pp. 644-54, 1978.
20. O. Kubo, T. Ido, and H. Yokoyama, "Properties of Ba Ferrite Particles for Perpendicular Magnetic Recording Media", *IEEE Trans. Magn.*, vol. MAG-18, 1122-4, 1982.
21. J.C. Mallinson, "The Foundations of Magnetic Recording", *Acad. Press*, 1987.
22. Head/Media Technology Review, Chairmen: D. Waid, Peripheral Research Corp. and D. Mann, Don Mann Magnetics, Nov. 1988.
23. P.P. Zapponi, "Method of Manufacturing a Magnetic Recording Medium by Electrodeposition", U.S. Patent: 2-619-454, 1952.
24. T.H. Bonn and D.C. Wendell, Jr., "Electrodeposit of a Magnetic Coating", U.S. Patent: 2-644-787, July 7, 1953.
25. A. Brenner and G.E. Riddell, "Nickel Plating on Steel by Chemical Reduction", *J. Res. NBS*, vol. 37, pp. 31-4, July 1946.
26. R.D. Fisher and W.H. Chilton, "Preparation and Magnetic Characteristic of Chemically Deposited Co for High Density Storage", *J. Electrochem. Soc.*, vol. 100, pp. 485-90, 1962.
27. J. Judge, J. Morrison, D. Spiliotis, G. Bate, "Magnetic Properties and Corrosion of Thin Electroless CoP Deposits", *J. Electrochem. Soc.*, vol. 112, p. 681-4, 1965.
28. G. Bate, D. Spiliotis, J. Alstad, and J. Morrison, "Magnetization Reversal in High Coercivity Cobalt Films", *Proc. 1964 Conf. on Magnetism, Phys. Soc.*, pp. 816-9, 1965.
29. Y. Suganuma, H. Tanaka, M. Yanagisawa, F. Goto, and S. Hatano, "Production Process and High Density Recording Characteristics of Plated Disks", *IEEE Trans. Magn.*, vol. MAG-18, pp. 1215, 1982.
30. K. Yoshida, T. Yamashita, and M. Saito, "Magnetic Properties and Media Noise of CoNiP Plated Disks", *J. Appl. Phys.*, vol. 64, pp. 270-5, July 1988.
31. T. Osaka, I. Koiwa, Y. Okabe, H. Matsubara, A. Wada, F. Goto, and N. Shiota, "Complete Magnetic Anisotropy Films for Perpendicular Recording Prepared by an Electroless Plating Method", *Bull. Chem. Soc. Japan*, vol. 58, pp. 414-9, 1985.

32. H. Sugaya and A. Tomago, "Metal Evaporated Tape", MMIS Symposium on Magnetic Media Manufacturing Methods, May 25, 1984.
33. K. Shinohara, H. Yoshida, M. Odagiri, and A. Tomago, "Columnar Structure and Some Properties of Metal Evaporated Tape", IEEE Trans. Magn., MAG-20, pp. 824-2, 1984.
34. R. Sugita, T. Nambu, and Y. Sakamoto, "Magnetic Prop. of Vac. Dep. CoCr Perpendicular Media & Rec. Performance" IEEE Trans. Magn., vol. MAG-23, pp. 2449-54, 1987.
35. O. Kitakami, Y. Ogawa, H. Fujiwara, F. Kugiya, and M. Suzuki, "The Effect of Initial Growth Layer on Magnetic Properties of CoCr Films", IEEE Trans. Magn., vol. MAG-24, pp. 2353-5, 1988.
36. K. Honda, R. Sugita, N. Echigo, Y. Sakamoto, and Y. Murakami, "Surface Oxidation of CoCr Evaporated Films", IEEE Trans. Magn., vol. MAG-24, pp. 2664-6, 1988.
37. R. L. Comstock and E. B. Moore, "Ferrite Film Recording Surfaces for Disk Recording", IBM J. Res. & Dev., v. 18, pp. 556, 1974.
38. N. Ingaki, S. Hattori, Y. Ishii, A. Terada, and H. Katsuraki, "Ferrite Thin Film for High Recording Density", IEEE Trans. Magn., MAG-12, pp. 785, 1976.
39. S. Yoshii, O. Ishii, S. Hattori, T. Nakagawa, and G. Ishida, "High Density Recording Characteristics of Sputtered Gamma Ferric Oxide", J. Appl. Phys., vol. 53, pp. 2556-60, 1982.
40. M. Yanagisawa, N. Shiota, H. Yamaguichi, and Y. Suganuma, "Corrosion-Resisting CoPt Thin Film Medium for High Density Recording", IEEE Trans. Magn., vol. MAG-19, pp. 1638, 1983.
41. R. A. Baugh, E. S. Murdock, and B. R. Nata-
rajan, "Measurements of Noise in Magnetic Media", IEEE Trans. Magn., vol. MAG-19, pp. 1722, 1983.
42. S. Iwasaki, Y. Nakamura, and K. Ouchi, "Perpendicular Magnetic Recording with a Composite Anisotropy Film", IEEE Trans. Magn., vol. MAG-15, pp. 1456, 1979.
43. S. Yamamoto, Y. Nakamura, and S. Iwasaki, "Extremely High Bit Density Recording with Single-Pole Perpendicular Head", IEEE Trans. Magn., MAG-23, pp. 2070, 1987.
44. J. P. Lazzari, I. Melnick, and D. Randet, "Thin Evaporated Films with High Hc", IEEE Trans. Magn., MAG-3, pp. 205, 1967.
45. J. Daval and D. Randet, "Electron Microscopy on High Hc CoCr Composite Films", IEEE Trans. Magn., MAG-6, pp. 768, 1970.
46. W. T. Maloney, "Sputtered Multilayer Films for Digital Magnetic Recording", IEEE Trans. Magn., vol. MAG-15, pp. 1135, 1979.
47. T. Yamada, N. Tani, M. Ishikawa, Y. Ota, K. Nakamura, and A. Itoh, "CoNiCr/Cr Sputtered Thin Film Disks", IEEE Trans. Magn., vol. MAG-21, 1429, 1985.
48. R. D. Fisher, J. C. Allan, and J. L. Pres-
sesky, "Magnetic Properties and Longi-
tudinal Recording Performance of Corro-
sion-Resistant Alloy Films", IEEE Trans.
Magn., vol. MAG-22, pp. 352, 1986.
49. J. A. Christner, R. Tanjan, R. L. Peterson
and J. I. Lee, "Low-Noise Metal Medium
for High-Density Longitudinal Recording"
J. Appl. Phys., vol. 63, pp. 3260-2, 1988.
50. Y. Shiroishi, Y. Matsuda, K. Yoshida, H.
Suzuki, T. Ohno, N. Tsumita, M. Ohura,
and M. Hayashi, "Read and Write Charac-
teristics of Co-Alloy/Cr Thin Films for
Longitudinal Recording", IEEE Trans.
Magn., vol. MAG-24, pp. 2730-2, 1988.
51. N. Tani, M. Hashimoto, Y. Murata, M.
Ishikawa, Y. Ota, and K. Nakamura,
"Effects of Substituted Elements Into
the Cr Layer on CoNiCr/Cr Sputtered Hard
Disk", HA-8, Intermag Conference, 1989.
52. Y. Shiroishi, Y. Matsuda, S. Hishiyama,
H. Suzuki, T. Ohno, N. Tsumita, M. Ohura,
and M. Hayashi, "Read and Write Charac-
teristics of CoNiZrM/Cr Thin Films",
BA-10, Intermag Conference, 1989.
53. Y. Hsu, J. Sivertsen, and J. H. Judy,
"Effective Epitaxial Thickness of RF
Sputtered CoCrTa/Cr Films", PMRC, 1989.
54. L. T. Romankiw and P. Simon, "Batch Fabri-
cation of Thin Film Magnetic Recording
Heads", IEEE Trans. Magn., MAG-11, 50, 1975.
55. R. E. Jones, Jr., "IBM 3370 Film Head De-
sign and Fabrication", IBM Disk Storage
Technology, vol. GA26-1665-0, pp. 6, 1980.
56. M. Hanazono, S. Narishige, K. Kawakami,
N. Saito, and M. Takagi, "Fabrication of
a Thin Film Head Using Polyimide Resin
and Sputtered NiFe Film", J. Appl. Phys.,
vol. 53, pp. 2608, 1982.
57. T. J. Szczec, "Analytic Expressions for
Field Components of Nonsymmetrical Fi-
nite Pole Tip Length Magnetic Head Based
on Measurements of Large-Scale Models",
IEEE Trans. Magn., MAG-15, pp. 1319, 1979.
58. S. Iwasaki and Y. Nakamura, Y. Yamamoto,
and K. Yamakawa, "Perpendicular Recording
by a Narrow Track Single Pole Head", IEEE
Trans. Magn., vol. MAG-19, pp. 1713, 1983.

59. S.E. Lambert, I.L. Sanders, A.M. Patlach, and M.T. Krounbi, "Recording Characteristics of Submicron Discrete Magnetic Tracks", IEEE Trans. Magn., vol. MAG-23, pp. 3690, 1987.
60. J. Hokkyo, K. Hayakawa, I. Saito, and K. Shirane, "A New W-Shaped Single-Pole Head and a High Density Flexible Disk Perpendicular Magnetic Recording System" IEEE Trans. Magn., vol. MAG-20, pp. 72, 1984.
61. K. Yamada, T. Maruyama, H. Tanaka, H. Kaneko, and S. Ito, "A Thin Film Head for High Density Magnetic Recording Using CoZr Amorphous Films", J. Appl. Phys., vol. 55, pp. 2235, 1984.
62. R. Hunt, "A Magnetoresistive Readout Transducer", IEEE Trans. Magn., vol. MAG-7, pp. 150, 1977.
63. T. Shinohara, K. Noguchi, H. Iwata, S. Suwabe, and T. Nishiyama, "Recording Characteristics of MIG Heads", IEEE Trans. Magn., vol. MAG-24, 2626-8, 1988.
64. D. Dressler and J.H. Judy, "A Study of Digitally Recorded Transitions in Thin Magnetic Films", IEEE Trans. Magn., vol. MAG-10, 674-7, 1974.
65. T. Chen, "The Micromagnetic Properties of High-Coercivity Metallic Thin Films and Their Effects on the Limit of Packing Density in Digital Recording", IEEE Trans. Magn., MAG-17, pp. 1181-91, 1981.
66. H.C. Tong, R. Ferrier, P. Chang, J. Tzeng, and K.L. Parker, "The Micromagnetics of Thin Film Disk Recording Tracks", IEEE Trans. Magn., vol. MAG-20, pp. 1831, 1984.
67. N. R. Belk, P.K. George, and G.S. Mowry, "Noise in High Performance Thin Film Longitudinal Magnetic Recording Media", IEEE Trans. Magn., MAG-21, pp. 1350-5, 1985.
68. P.S. Alexopoulos and R.H. Geiss, "Micromagnetic and Structural Studies of Sputtered Thin Film Recording Media", IEEE Trans. Magn., vol. MAG-22, pp. 566-9, 1986.
69. H. Aoi, M. Saitoh, N. Nishiyama, R. Tsuchiya, and T. Tamura, "Noise Characteristics in Longitudinal Thin Film Media", IEEE Trans. Magn., MAG-22, 895-7, 1986.
70. H. Aoi, R. Tsuchiya, Y. Shiroishi, and H. Matsuyama, "A Study of Thin Film Noise by Magnetic Domain Observation", IEEE Trans. Magn., MAG-24, pp. 2715-7, 1988.
71. T.A. Nguyen, P.S. Alexopoulos, C. Huang, S.E. Lambert, and I.L. Sanders, "Domain Structures in Thin Film Discrete Tracks" IEEE Trans. Magn., MAG-24, pp. 2733-5, 1988.
72. T. Yogi, G.L. Gorman, C. Hwang, M.A. Kalkalec, and S.E. Lambert, "Dependence of Magnetics, Microstructures, and Recording Properties on Underlayer Thickness in CoNiCr/Cr Media", IEEE Trans. Magn., vol. MAG-24, pp. 2727-9, 1988.
73. J.G. Zhu and H.N. Bertram, "Micromagnetic Studies of Thin Film Metallic Films", J. Appl. Phys., vol. 63, pp. 3248-53, 1988.
74. R.P. Ferrier, F.J. Martin, T.C. Arnoldussen, and L.L. Nunnelle, "Lorentz Image-Derived Film Media Noise", IEEE Trans. Magn., MAG-24, pp. 2709-11, 1988.
75. T. Chen and T. Yamashita, "Physical Origin of Limits in the Performance of Thin Film Longitudinal Recording Media", IEEE Trans. Magn., MAG-24, pp. 2700-5, 1988.
76. I. Tagawa and Y. Nakamura, "An Analysis of Perpendicular Magnetic Recording by a Newly Developed 2D-FEM Combined with a Medium Magnetization Model", KA01, Intermag Conference, 1989.
77. K. Yoshida, T. Okuwaki, N. Osakabe, H. Tanabe, Y. Horiuchi, T. Matsuda, K. Shinagawa, I. Tonomura, and H. Fujiwara, "Observation of Recorded Magnetization Patterns by Electron Holography", IEEE Trans. Magn., MAG-19, pp. 1600-5, 1983.
78. I.R. McFadyen, "Implementation of Differential Phase Contrast Lorentz Microscopy on a Conventional Transmission Electron Microscope", J. Appl. Phys., vol. 64, pp. 6011-3, 1988.
79. K. Mitsuoka, S. Sudo, N. Narishige, M. Hanazono, and Y. Sugita, "Magnetic Domains of Permalloy Thin Film Heads Observed by Spin-Polarized SEM", IEEE Trans. Magn., MAG-23, pp. 2155-60, 1987.
80. P.V. Koeppel and M.H. Kryder, "Direct Observation of the Dynamic Magnetic Action in Metal-In-Gap Recording Heads", EQ-16, Intermag Conference, 1989.
81. D. Rugar, H.J. Mamin, J.E. Stern, R.E. Fontana, Jr., P. Kasiraj, I. McFadyen, and S. Lambert, "Magnetic Force Microscopy Techniques and Applications", KB-4, Intermag Conference, 1989.
82. M. Yanagisawa and Y. Motomura, "An Ultra-micro Indentation Hardness Tester and its Application to Thin Films", Lubrications Eng., vol. 43, pp. 52-56, 1987.
83. C.M. Mate, M.R. Lorenz, V. Novotny, I.L. Sanders, and L.J. Lin, "Tribological Studies of Storage Media by Atomic Force Microscopy", GA-7, Intermag Conference, 1989.