Magnetic Thin Films for Information Storage

George J-S Gau

In most storage technologies, the two critical components are the recording head and the recording medium; hence, improvements in storage media go hand in hand with improvements in read/write head technology. Thin films are becoming the dominant medium chosen to meet the burgeoning demand for information storage, and thin-film technology has been transferred to the read/write heads as well. Materials science plays an important role in correlating the structure, properties and processing of thin-film magnetic materials for both applications.

INTRODUCTION

The 1980s hosted an explosion of growth in the computer industry, which also produced an insatiable need for data storage capacity. However, with paper still king, less than 5% of all information is stored in a retrievable and rewritable magnetic medium. Of all electronic storage technologies, magnetic recording is the predominant means of information storage, because it has thus far maintained a sufficient price/performance ratio to remain ahead of the emerging competition from optical recording and the wafer-scale integration of semiconductor random access memory (i.e., the solid-state disk).

Meeting these mounting challenges and anticipating the requirements of tomorrow’s advanced storage systems have sparked intensive research and development activities in every branch of magnetic recording technology, including the recording head, recording medium, recording mode, recording processes and the theory of signals. The recording head and medium are the most critical components. Their technology is rooted in fundamental magnetism and applied magnetics, and the metallurgical disciplines are heavily involved.

THE DESIGN APPROACH

In conventional longitudinal recording, the recording process transfers the input signal into a variable magnetization pattern stored in the medium. The medium consists of small permanent magnets, each representing binary information (i.e., either “zero” or “one”) with alternative magnetization parallel to the medium’s surface.

Magnetic recording is poorly understood due to the nonlinear and hysteretic magnetization process. The recording process, on the other hand, is almost fully grasped. According to the reciprocity principle, the width of the output pulse measured at one-half of the maximum amplitude level \( PW_{50} \), which affects both the resolution and bit shift, is related to the parameters of the head / medium system and given by:

\[
PW_{50} = \sqrt{4(a + d)(a + d + t)}
\]

where \( d \) is the separation distance between head and medium, \( g \) is the length of the recording gap, \( t \) is the thickness of the recording medium, and \( a \) is the transition width.

The output pulse \( E(x) \) takes on the Lorentzian form, as follows:

\[
E(x) = \frac{1}{1 + \left( \frac{2x}{PW_{50}} \right)^2}
\]

The design of a given recording system is then simply aimed at providing an areal density as high as possible per recording surface, by optimizing both the system parameters such as various physical dimensions and the magnetic characteristics of the head and medium, and their interactions. As an example, a small transition width (a) would lead to a sharp pulse shape and have lower noise. This characteristic length is related to the magnetic properties of the medium as follows:

\[
a = \frac{[M_r t]^{1/3}}{H_c}
\]

where \( H_c \) is the coercivity, \( t \) is the thickness, \( M_r \) is the remnant magnetization, and \( k \) is a constant dependent on the criterion of transition used, and is about 0.5 for the arc tangent magnetization model.

To provide perspective, Figure 1 depicts chronologically the progress made in the linear, track, and areal densities since the introduction of the magnetic storage disk technology nearly four decades ago, using mainly the IBM drive as the indicator.

Linear Density

Because the achievable linear density in longitudinal recording is mainly limited by the demagnetizing field associated with the recorded bits, improvements in the recording media, such as the now-predominant cobalt-doped gamma ferrite and the emerging pure metallic particles, have been accomplished mainly by increasing the coercivity of the media to withstand the demagnetizing field, and/or by reducing the thickness of the magnetic layer. However, particulate media are dispersed in an organic binder and magnetic particles are irregular in shape, thus limiting the attainable coercivity and the thinness of the magnetic layer that can be coated. As the thickness is further reduced, problems in coating uniformity, surface defects, and, most importantly, reduced output signal are the overriding concerns. Therefore, there is a strong motivation to develop new thin-film media that can be made very thin, in the range of 50–100 nm, and still have very high magnetization.

Thin-film media are logically divided into two categories: flexible media with a polyester substrate, and hard disks with an amorphous Ni-P coated Al-Mg alloy substrate or the emerging ultra-smooth glass substrates. Interestingly enough, metallic films based on the ferromagnetic transition metals (Fe, Co and Ni) and their alloys under the normal thin film preparatory conditions tend to have very low values of coercive force, typically below 300 Oe, and are therefore unsuitable for recording applications.

There are several solutions to this problem. One is to prepare the thin-film medium under the oblique deposition condition, such that an induced magnetic anisotropy is developed. The metal-evaporated (ME) videotape used in the Hi8 (8 mm) camcorder typifies this technology. Also, with a suitable underlayer such as chromium, the sputtered cobalt-base alloy films are widely applied in hard disks. Recently, a single layer system with the addition of noble alloy elements such as platinum was shown to possess high coercivity for recording applications.

There is another solution. This is to prepare the thin-film medium under the oblique deposition condition, such that an induced magnetic anisotropy is developed. The metal-evaporated (ME) videotape used in the Hi8 (8 mm) camcorder typifies this technology. Also, with a suitable underlayer such as chromium, the sputtered cobalt-base alloy films are widely applied in hard disks. Recently, a single layer system with the addition of noble alloy elements such as platinum was shown to possess high coercivity for recording applications.

Track Density

In contrast to the linear density, several factors have been attributed to the slower-than-expected progress made in the track density. A track pitch of about 1.6 μm is quite common for the optical recording rival, in sharp contrast to the 12 μm track pitch for the state-of-the-art magnetic disk drive with 790 tracks/cm.

Meeting the demands for higher track density
density for a given medium has necessitated the development of thin-film magnetic heads. Along with the array potential and better controlled geometry and dimensions, magnetic thin-film heads represent the ideal answer to the problems of precision machining associated with bulk-type monolithic and/or composite ferrite heads for narrow track and multi-track applications with a small track pitch. Thin-film heads also meet the need for magnetic materials with higher permeability over a wider frequency range and higher saturation magnetization in magnetizing recording media with high coercivities.

The thin-film head (TFH) is, basically, a solid-state analog of the conventional bulk-type head, which consists of a ring-shaped magnet with a gap in it and coils wound around the core. A variety of thin-film head designs based upon two architectures, horizontal and vertical, have evolved since its inception in the early 1960s. In the vertically configured thin-film head, the mainstay of the industry, the films which form the magnetic core are perpendicular to the recording medium. Typical head build processes for a two-layer, thirty-turn thin-film head—which consists of a ceramics substrate, lower magnetic core, gap oxide, polymer insulator, conductive coils, upper magnetic core, and passivation thick oxide layer—may account for more than a dozen masking levels. The large number of steps required to produce a recording head is reminiscent of the tedious process needed to manufacture semiconductor devices. A comparison of the processing issues between the semiconductor dynamic random access memory (DRAM) and TFH transducer is shown in Table I.

**MATERIALS SCIENCE OF THIN FILMS**

Phase transformation, residual stresses, interdiffusion, segregation, grain growth during annealing and thermal cycling during device fabrication represent areas of interest in generic thin-film metallurgy, which differs from what is well known about the bulk system.

**Thin-Film Media**

The oblique-evaporated ME film owes its characteristics to a magnetic anisotropy induced by processing; its microstructure consists of an array of fine, slanted and isolated columns. Convergent electron diffraction shows that these columns are single crystals; the preferred texture (i.e., the [0001] c-axis) does not coincide with the columnar axis of the particle. Lorentz microscopy has shown the existence of stripe domains arising from the out-of-the-plane magnetic anisotropy. The formation and switching dynamics of the stripe domains depend on composition and the film’s thickness.

This type of domain state is believed to contribute to low noise levels.

For hard disks, sputtered single-layer magnetic films, such as Co-Ni-Pt and Co-Pt, and double-layer Co-Ni-Cr or Co-Cr-Ta with a chromium underlayer, represent another class of thin-film medium. The microstructure of these films has been extensively characterized using analytical electron microscopy, and exhibits a similar morphology featuring very fine grains. Although the role of chromium was thought to enhance the epitaxial growth with the preferential axis lying in the film plane, recent high-resolution lattice images have shown that grain size, defects and localized ordering can be attributed to the unique magnetic properties. The high coercivity in the Co-Pt system is attributed to the mixture of hexagonal close-packed and face-centered cubic phases, and to high crystalline anisotropy.

Although development activities are found in sputtered oxide films featuring a very low noise power spectrum (e.g., gamma ferrite and barium ferrite), additional post heat-treatment and problems dealing with the control of stoichiometry, and magnetic instability in oxide films have limited their acceptance in the marketplace.

Remarkable improvement in linear density has been accomplished in recent years by improving the recording medium’s ability to support shorter transitions. This is done mainly through a better grasp of the recording physics and micromagnetics of the thin film. Magnetic media under conditions which lead to a morphology of isolated particles (i.e., high argon pressure and high substrate temperature) will have a better resolution and higher signal-to-noise ratio than their quasi-continuous film counterpart.

Along with a thorough characterization of microstructure using analytic electron imaging and spectroscopic tools, several innovative magnetic domain imaging and probing techniques, such as differential phase contrast (DPC) Lorentz microscopy and scanning electron microscopy for polarization analysis (SEMPA), have also been developed lately to further advance the understanding about micromagnetics at an unprecedented spatial resolution level. The DPC Lorentz microscopy technique permits a quantitative study of the microscopic magnetization reversal process in various thin-film media dynamically. Furthermore, the magnetization vortex state and its formation in the transition region of head-on magnetizations in recorded thin-film media have been extensively detailed by this technique, contributing significantly to the understanding about the probable noise and coercivity mechanisms.

**Figure 1.** The areal, linear and track densities of representative hard disk drives as a function of the year. Also marked are the key milestones of technologies: the introduction of vertical recording, the thin-film head, the magneto resistance (MR) head, and thin-film metallic media. BPI is bits per inch, and TPI is tracks per inch.