

Optical data storage media

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In this paper, we review many of the technical issues that must be addressed in developing high-quality optical disk recording media. The geometric design of tracking grooves and embossed data on the disk substrate must be optimized to the characteristics of the optical drive to support robust data seeking, track following, and data addressing. To ensure adequate recording performance and drive compatibility, we have used modeling to optimize the media thin-film structure for proper optical, thermal, and magnetic characteristics. Because low substrate birefringence is a necessary media characteristic for high recording densities, we discuss measurements which assess whether birefringence has been adequately controlled in disk production. Testing is used throughout media development and manufacture to measure that the quality goals of the design are achieved. The mechanical integrity of the disk and its cartridge, particularly for autoload libraries, is confirmed by load/unload stress testing. Media life and data archivability are established by a combination of time-zero and accelerated life stress tests of media mechanical and recording performance. This attention to a broad range of technical details is essential to ensure reliable storage of data on removable optical disk media.

Introduction

The storage of data on disks by optical means is claimed by industry analysts to be the most significant growth

segment of the data storage industry of the 1990s. The 1980s saw the appearance of the first products for optical data storage, but acceptance of the new technology developed slowly. The particular strengths of optical products in the storage hierarchy have emerged in the first half of the decade. Users are attracted by a favorable mix of attributes—low cost per bit, archivability and high reliability, high capacity, high volumetric density, media removability and interchangeability, high data rates, and good accessibility. Awareness of the advantages of an optical disk (OD) for on-line and near-line random-access storage of large volumes of data, especially images and documents, is becoming established. A wide range of OD media products is ready to meet the burgeoning demand for electronic storage of information at ever-diminishing cost.

Following an overview of the types of OD media and their characteristics and formats, we discuss the methods of design and testing that support the product specifications. In OD technology, design is extensively supported by modeling and simulation, while a thorough array of testing protocols establish standards of performance that must be ensured over the life of the manufactured product. The OD product for data storage is complex, and production of a high-quality component requires optimum design coupled with exacting process control. We also look ahead to ways in which more demanding future designs will dictate extension and growth of design and testing discipline.

Optical disks are interchangeable components that generally must conform to industry standards. However, what is frequently not appreciated is that international standards do *not* guarantee overall product quality. They provide for OD interchange combined with a minimum level of acceptable performance. It has become clear with

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the early evolution of OD data storage products that each successive generation embodies a significant increase in complexity. This manifests itself in a greater degree of differentiation in performance levels across a population of OD producers. This differentiation results from growth in the number of performance attributes that matter and in the degree of difficulty in meeting each more stringent requirement. Thus, even in an arena where one is developing and manufacturing a standardized, interchangeable recording component, there is considerable margin for product differentiation in quality and performance.

Optical disk characteristics

There are three types of ODs for data storage [1, 2]. The simplest and the first to have high-volume impact on the market is read-only memory (ROM). The most pervasive ROM format is the data storage derivative of the audio compact disc (CD) format, called CD-ROM. This is a simple, low-cost design—a hubless, uncartridged, single-sided 120-mm-diameter disk with read-only data embossed into the plastic substrate at the point of manufacture. A more expensive ROM solution (called OD-ROM—optical disk ROM) offers performance and ruggedness commensurate with high-performance data storage. The two other data storage OD types are user-writable—called write-once, read-many (WORM), and rewritable or erasable. WORM is implemented in two important ways. The first (we call it “permanent WORM”) uses indelible physical marking on the disk, often involving material ablation or irreversible phase change. A second type of WORM called CCW (continuous composite write-once) which has recently appeared uses a rewritable medium, but is implemented with optical drive software inhibitors to rewrite (unfortunately, the inhibitors could possibly be defeated by a knowledgeable user). Rewritable ODs are today based mainly on thermally assisted magnetic recording on a thin film combined with magneto-optic (MO) readout. Alternate approaches for rewritable optical storage use phase-change materials or somewhat complicated dye systems that use contrast and/or topographical modifications under the action of a focused laser beam. The recent PD¹ optical drive is an example of a successful rewritable phase-change system that has reached the marketplace.

The CD-ROM format has been extended to WORM (CD-R) and rewritable (CD-E) embodiments with moderate success. Recently, there has been much expectation of the next-generation CD (currently referred to as “digital versatile disk,” or DVD), which would support much higher data density and throughput, as well as accommodating a wider range of multimedia

applications (video, audio, computer data, publication, etc.). It is expected to become prevalent in the marketplace by 1997 or 1998, and will likely evolve from ROM to WORM and to erasable versions later this decade.

Figure 1 shows some of the important characteristics of the OD package and disk structure, as well as the basic recording process on MO disks. Figure 1(a) shows a cartridged 130-mm optical disk (a typical MO or WORM format based on an international standard [3]). The cartridge provides protection for the interchangeable data disk while it is inserted or removed from an optical drive, or when the disk is being transported outside the drive. Figure 1(b) presents the layout of the embossed surface topography of a disk formatted with the continuous composite servo (CCS) structure. Depicted are the tracking grooves, the track “land” on which data are recorded, and an example of an embossed data pit in the land region. Figure 1(c) shows a common thin-film stack that would be deposited over the substrate topography of Figure 1(b), including the MO alloy in which rewritable data are stored in thermomagnetically written domains. Figure 1(d) illustrates schematically how the write, read, and erase processes in recording on MO materials are carried out in the simplest possible mode. Recording and erasure are a form of magnetic recording assisted by the application of thermal energy to raise the temperature of the recording material close to or above its magnetic switching point. Readout is performed by exploiting the magneto-optic effects which occur when polarized light interacts with magnetized ferro- or ferrimagnetic material: The polarization of linearly polarized light is rotated slightly when the light is transmitted through (MO Faraday effect) or reflected from (MO Kerr effect) a magnetic material. The direction of polarization rotation depends on the orientation of the material magnetization.

Design and modeling

Optimum design in optical storage has often been achievable because the basic physics of the writing, erasing, and readout processes is reasonably well understood. The mathematical analysis is feasible and has led to the development of fairly standard models (see particularly Chapter 10 of [2]). Insofar as the light interaction with the disk is concerned, workable approximations are available.

Several major development activities are central to the creation of optical data storage media products. Among the subsystems of the media, we discuss the modeling-testing interaction for

- Embossed substrate groove and pit geometries and servo signal effects.
- Substrate birefringence causing servo and readout effects.

¹ The acronym “PD” currently has no single agreed-upon meaning.

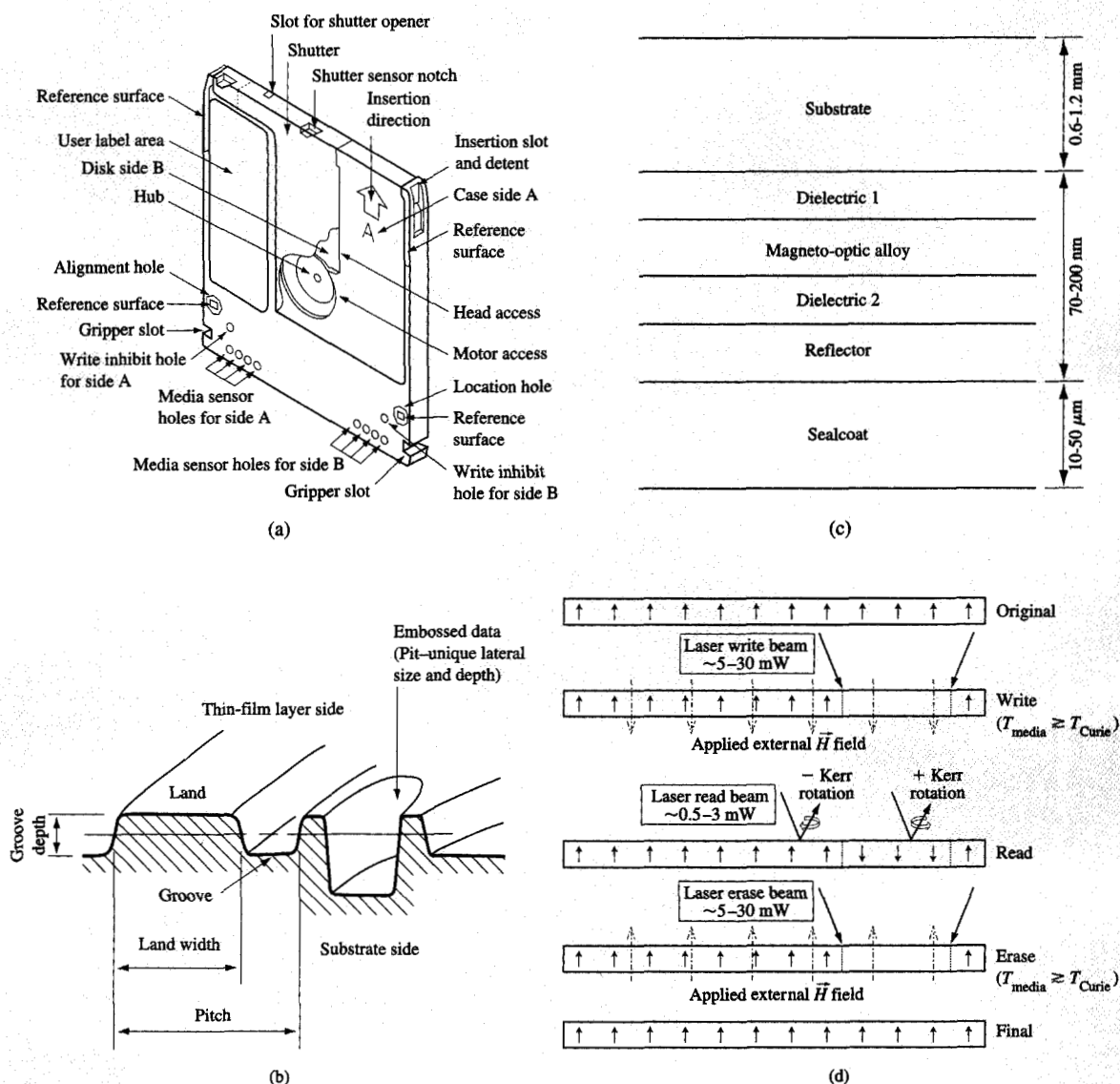


Figure 1

Optical disk cartridge and disk features, and an overview of the recording processes: (a) 130-mm optical data disk cartridge. (b) Embossed CCS format on disk substrate. (c) Quadrilayer film stack on a magneto-optical disk. (d) The process of writing, reading, and erasing information on a magneto-optic disk.

- MO disk thin-film structure and optical/MO performance.
- Thermal behavior of MO thin films in write/erase/read.
- Magnetic behavior of MO thin films in write/erase/read.

• Modeling and design of tracking servo signals

With each new optical media product generation come rapid improvements in recording performance and density

that require a reoptimization of disk parameters. Considering the embossed groove and format data information on the surface of the disk substrate, a few design goals are clear:

- Signals from the grooves for the tracking servo system must have adequate signal-to-noise ratio (SNR) and uniformity over the disk.

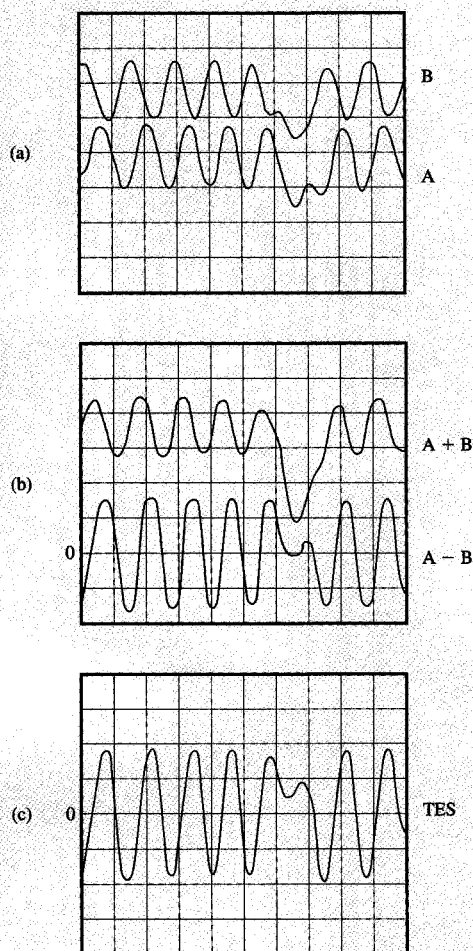


Figure 2

Optical disk tracking signals taken from oscilloscope traces: (a) Track crossing servo signals for detectors A and B of a split photodetector pair. (b) Sum and difference signals from the detectors of (a). (c) Tracking error signal $TES = (A - B)/(A + B)$.

- The tracking signals must be free of interference from embossed data pits in the land region, particularly during track crossing while data seeking.
- The embossed data must be accurately placed and the signal levels must be adequate and uniform.

One area of concern is optimization of the geometric design of tracking grooves and embossed data on the disk substrate to support good seek performance in the drive. Guidance in the design by scalar diffraction modeling [4], supplemented with experimentally measured geometrical information, has proven to be an essential key to

development of the highest-quality optical disks. The scalar diffraction approximation is believed to be reasonable for numerical apertures < 0.6 [4].

Basic to the success of the modeling effort is an accurate measurement of the pit/groove profile. An atomic force microscope (AFM) is capable of measuring the surface topography of an optical disk substrate to a small fraction of the wavelength of the laser light [5]. The surface topography is input to a diffraction model which describes the scattering of laser light from the surface and calculates the tracking servo signals. The signals are then compared to the actual tracking servo signals measured from the substrate on an optical disk tester. The agreement between calculated and measured signals is used to verify the model. An example is given below. Subsequently, the model is used to identify the best design characteristics.

• Tracking error signal measurements

The tracking error signal (TES) is a position error signal used for servo control of the focused light spot for data track following. In optical recording, a data track typically is recorded on a "land" region between grooves embossed in the plastic disk substrate. These tracking grooves normally spiral inward or outward on the disk covering the entire radial recording band, with the groove pitch measuring 1–2 times the light wavelength. As the focused light beam wanders in the land region between tracking grooves, diffracted light reflected back to a split detector causes varying signal imbalance between the halves of the detector. The TES is the difference of the signals from the two halves of a split light detector divided by their sum. A feedback control system holds the focused spot at the position of land center where the TES is zero. A fast and accurate tracking servo system using the TES is the only means for controlling misregistration of the read/write laser beam about the data track center. Further, the TES provides a periodic signal for detecting track crossings as the laser beam translates radially on a spinning disk, so the TES is critical for the seeking of information at different radii on the storage disk. Both sum and difference signals from the split photodetector are typically available for monitoring or control.

The tracking servo signals can be measured on a precision test stand with the disk stationary and the head moving radially. The head motion is accomplished by driving the tracking offset with a sinusoidal voltage. The servo signals arise from light reflected from the disk falling on two halves (called A and B below) of a split photodetector. The photodetector is aligned so the split is along the track direction. Thus, as the head moves from the center of the track toward a groove, destructive phase interference from the groove reduces, preferentially, the intensity of light on the half of the detector over the

groove. This was shown most clearly in model calculations by Karis et al. [5] of the light intensity falling on each half of the photodetector as a function of head position.

- *Example of non-optimized design*

Misoptimization of the substrate embossed feature geometry can cause serious problems in the tracking servo signals. **Figure 2** shows tracking servo signals produced by the focused laser beam crossing tracks and occasional embossed pits during track seeking. The A and B signals in **Figure 2(a)**, arbitrarily offset with respect to one another, show a large modulation and are nearly out of phase. Also, there is some asymmetry associated with the asymmetry in pit geometry. In **Figure 2(b)**, the $A + B$ signal nearly goes to zero at the pit, while $A - B$ has almost no modulation. Finally, the TES signal in **Figure 2(c)** has a large peak-to-peak modulation in the groove-only region but a small modulation over the pit in the center of the land. The light scattering from the embossed pit is non-optimal in this design.

It is interesting to compare the resulting servo signals for this particular geometry to the 2X ECMA (European Computer Manufacturers Association) specification [3]. The ECMA specification puts several constraints on the range of these signals. The cross-track signal ($A + B$) must meet two specifications. Its peak-to-peak value normalized to its peak value on a land should be between 0.2 and 0.6—in this example it is 0.32. Its minimum magnitude normalized to its peak value on a land should be greater than 0.15—it is 0.18. The push-pull ratio ($A - B$ normalized to $A + B$ on land) should be between 0.4 and 0.65—it is 0.68, slightly out of specification. The TES signal should be between 0.65 and 1.05—it is 0.81 away from the pits, but it falls to 0.11 over the pits, where it should be >0.7 . The 0.7 value is TES uniformity, that is, the ratio of the TES over the pits to its value over a land region. Besides, the peak-to-peak value of signal A normalized to its peak land value should be >0.5 , and it is 0.8. In summary, most signals meet specification, but the TES signal in this sector mark region fails badly. The following sections address this deficiency.

- *Modeling results*

An example of the pit/groove geometry measurement by AFM is shown in **Figure 3**. The disk is formatted into 512 or 1024 user byte data sectors. Each sector includes a header region followed by the data region and ECC (error correction code). The header region begins with sector marks, which are long (code-violating) marks that identify the beginning of a sector. The sector marks are followed by the VFO (variable-frequency oscillator) and address marks. The VFO field is made up of short, almost circular, marks, as shown to the right of center in **Figure 3**. In this analysis we focus on the sector marks (an example is the

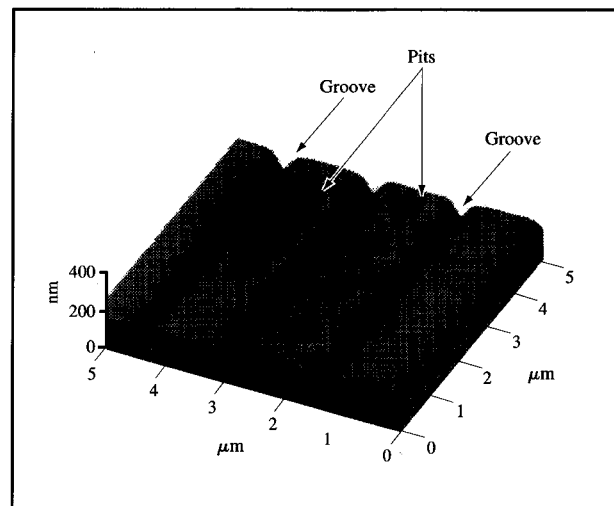


Figure 3

Atomic force microscope (AFM) picture of the surface of an optical disk showing grooves for tracking and embossed data pits for sector identification.

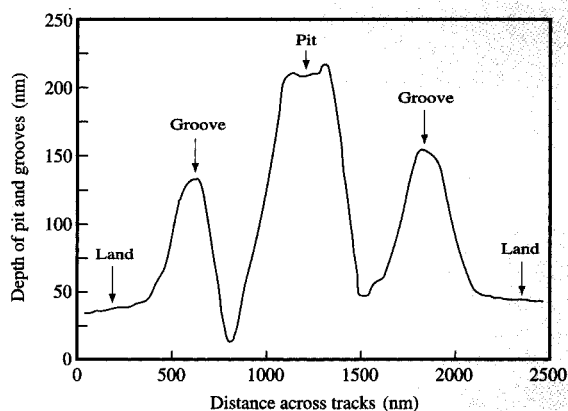


Figure 4

Cross-sectional line trace of a 2D AFM image in the disk radial direction showing a pit in the track land flanked by tracking grooves. The geometry is inverted in this figure—the highest point on the trace is the deepest part of the pit.

long mark left of center in **Figure 3**), since they produce the largest distortion in the TES. Also, since the sector marks are long compared to the beam diameter, no accuracy is lost by taking a radial profile through the sector mark (**Figure 4**) and replicating this in the third

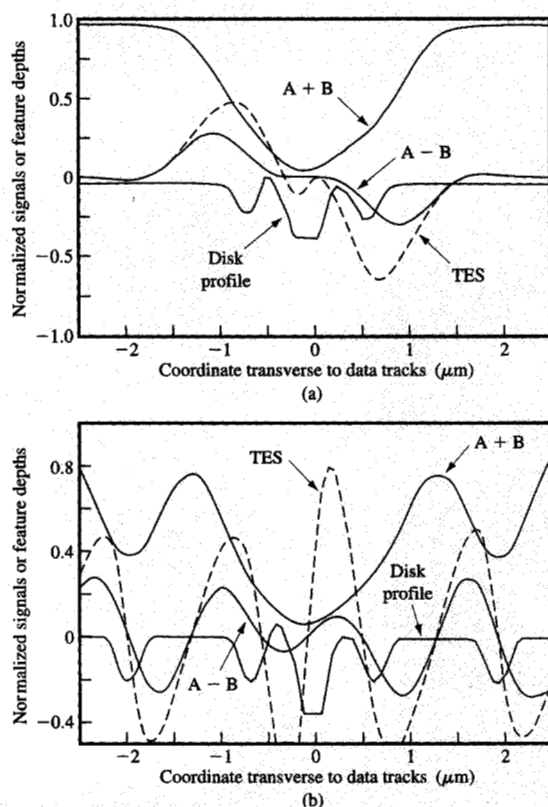


Figure 5

A radial profile of a disk track topography (as in Figure 4), along with the signals $A - B$, $A + B$, and $TES = (A - B)/(A + B)$: (a) An actual AFM radial disk profile and the corresponding signals. (b) An approximate but more ideal radial profile and the corresponding signals. Note the huge difference in the TES for the two cases. $A + B$ and $A - B$ are normalized to the value of $A + B$ from an ungrooved mirror region. The disk profile is expressed in depth units normalized by λ/n .

dimension to produce a 3D surface. Scalar diffraction calculations of the servo signals on this extended 2D geometry require less computing time than for a full 3D AFM surface as in Figure 3.

A scalar diffraction model [4] has been used to model the TES signal in the pit region using the measured AFM profiles. For some pit geometries, anything less than the true profile will not produce agreement with the measured TES signals. The reason for the difference is explained by the example in Figure 5. The graph in Figure 5(a) shows the AFM trace of the pit/groove geometry and the calculated servo signals. The graph in Figure 5(b) shows a simulated geometry, created from analytic functions and selected features (widths and depths) from the AFM trace, but the TES signal (dashed) is totally different. The reason

for this extreme sensitivity to geometry is that the $A + B$ signal is nearly zero in the pit region; therefore, any slight change in $A - B$ is amplified by division by $A + B$. It is critical to choose the best design space for the groove and pit geometry to avoid dramatic variations in the TES.

The sensitivity of the TES to the pit geometry is studied through a contour plot (Figure 6) of the TES as a function of the pit width and the pit depth. The pit depth has been normalized to the light wavelength (λ) within the substrate material (for this case, $\lambda/n = 520$ nm, where n is the substrate refractive index). In this plot, the region with the least sensitivity to changes in these parameters has narrow ($0.15 \mu\text{m}$) and deep ($0.45 \lambda/n$) pits. To verify this result, we have taken this nominal design point and modeled two cases—one with and one without "pit smear" (Figure 7)—a poor-fidelity replication of embossed pits that can occur during ejection of a freshly molded plastic substrate from the press with stamper die. The resulting TES signals do not change a great deal, even though the differences in $A - B$ and $A + B$ are significant. This is because $A + B$ is not close to zero for this pit geometry.

The good agreement for AFM-measured geometries between measured and modeled servo signals provides a high degree of confidence in the predictive ability of the model (Figure 7). It can be used to determine pit/groove design geometries that give good servo performance. The modeling for this case (Figure 6) suggests that we should move the design point toward narrower and deeper pits to avoid the extreme sensitivity of the TES signal due to slight changes in the pit geometry.

Controlling substrate birefringence

Birefringence is an optical property of a material whereby polarized light propagating in the material does so with different speeds depending on the direction of oscillation of its E -field vector (i.e., its polarization). An equivalent way to describe birefringence is to specify differences in the material refractive index n in various directions in a material. Birefringence is a key substrate parameter that must be controlled if satisfactory recording performance is to be achieved. We briefly describe birefringence, the two different types that can be distinguished by their effect on recorder performance, some secondary phenomena induced by birefringence, and some possible approaches to controlling the level of birefringence met in optical drives.

Optical anisotropy in molded plastic optical disk substrates can be sizable. (Birefringence in glass disks is negligible compared to that in injection-molded polymer disks.) For a local Cartesian coordinate system aligned with its z -axis normal to the disk plane, the x -axis tangential to the tracks, and the y -axis aligned in the radial direction, the birefringence in polycarbonate can be of the order $|n_x - n_y| \sim 20 \times 10^{-6}$, while

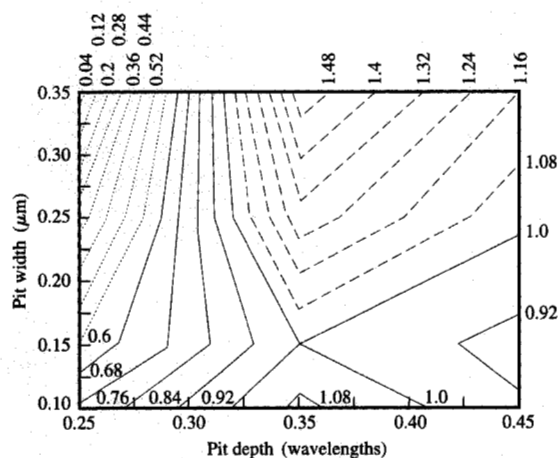
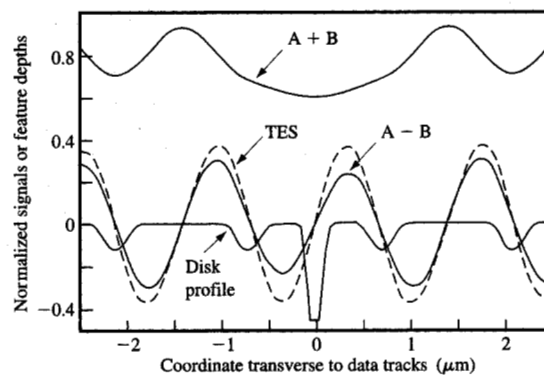


Figure 6

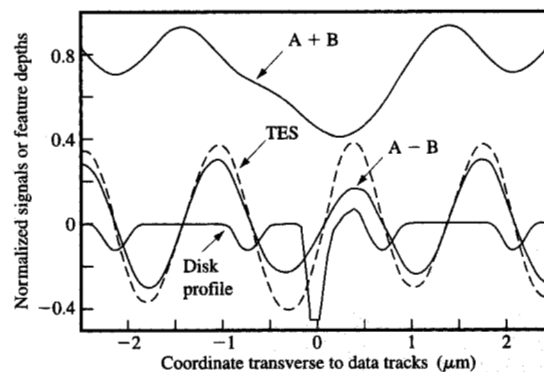
Contours of TES amplitude over the embossed pit versus pit width and pit depth; note the different units along the ordinate and abscissa.

$|n_x - n_z| \sim 500 \times 10^{-6}$. The former is called in-plane or lateral birefringence (LB), while the latter is called out-of-plane or vertical birefringence (VB) [6, 7]. A light wave traversing the substrate undergoes phase retardation according to the way in which its $\vec{E}$ components (i.e., its state of polarization) sample the corresponding components of the refractive index ellipsoid. For example, given a material with its index ellipsoid principal axes perfectly aligned with the Cartesian coordinates described above, a ray normally incident on the disk plane is sensitive only to LB, while a ray entering the disk surface obliquely may experience both LB and VB, the VB increasing with increasing angle of incidence.

The consequences of LB are well known in the optical recording industry [1, 2]. Essentially, birefringence introduces a phase shift between orthogonal polarization components of the light traversing the disk substrate. Since magneto-optic recording is based on detection of the small, induced, orthogonal polarization because of the Kerr/Faraday effect, perturbation of the phase relationship between the components of polarization parallel and perpendicular to the direction of incident polarization affects the MO signal level to first order. These effects are most evident in differential detection schemes which are widely used. Sensitivity to variable LB as a disk rotates causes MO signal baseline wander, variability in the RF MO signal amplitude, and degradation of the common-mode noise rejection of the detection channel. Generally speaking, variable LB degrades channel SNR in ways



(a)



(b)

Figure 7

A plot similar to that shown in Figure 5: (a) A "perfect" embossed pit without pit smear. (b) A "smeared" pit. Note the insensitivity of the TES to the pit imperfections at the design geometry chosen (see Figure 6).

that are difficult to compensate, so LB has long been controlled through standards specification (e.g., [3]) in optical data storage media to minimize its deleterious effects.

The principal problem caused by VB is the induction of astigmatism in the optical beam at the focal plane of the lens after passing through the substrate. This arises from the cumulative effect on the s- and p-polarization components of rays comprising the convergent beam. While it is theoretically possible to compensate an average level of astigmatism contributed by the disk substrate in the optical system of an optical drive, the problem arises, as it does with LB, from the *variability* of VB, both from disk to disk and across a given disk surface (because of process variability or material type variability). Furthermore, the astigmatism caused by the substrate may be of a complex sort because of substrate material defects or local stresses causing tipping of the index ellipsoid [6].

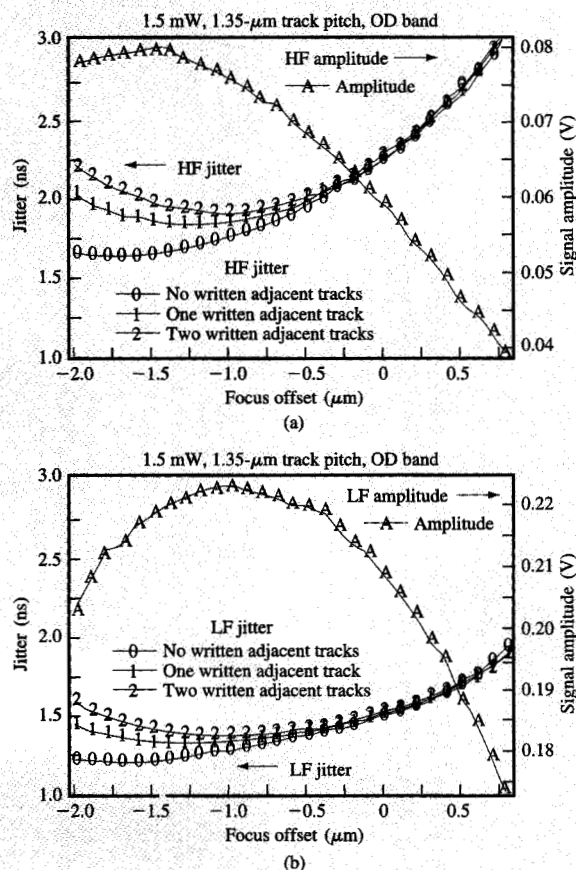


Figure 8

Signal amplitude and jitter behavior with focus offset: (a) High-frequency (3T) and (b) low-frequency (8T) pulse position modulation (PPM) signal amplitude and jitter versus focus servo offset; the jitter is shown for cases of zero, one, and two adjacent tracks written, and hence variable crosstalk coupling. The misalignment in focus position of the amplitude maxima and jitter minima is evidence for astigmatic aberration in the focused write/read beam, probably because of substrate vertical birefringence. This information plus the behavior of the TES with defocus shows that simultaneous optimization of focus setting for all of these signals with substrate vertical birefringence is unavailable.

Substrate-induced astigmatism in the focused light spot can have a strong impact on optical drive recording performance and random error rate, as follows. Astigmatism is a property of an optical system whereby a beam cannot be focused to the smallest spot size simultaneously in two perpendicular directions. Given a perfect optical head (no astigmatism), a perfect disk (no vertical birefringence), and no interaction between the

focus and tracking servo signals ("feedthrough"), the optimum focus occurs at a single axial position of the objective lens relative to the disk surface. The focal conditions of largest high-frequency (HF) amplitude (maximum resolution), largest low-frequency (LF) amplitude (maximum sensitivity), minimum write power (highest power density), minimum jitter (smallest optical spot size along the track), minimum crosstalk (smallest optical spot across the track), and maximum TES (best tracking error signal for tracking and seeking) all coincide. Any amount of defocus from this point degrades performance. This nearly ideal behavior is most closely observed on disks made with glass substrates (no VB). However, glass has other problems, notably cost, as discussed later.

With astigmatism, there exists no absolute optimum focus setting, and as a consequence, performance suffers. This "focus offset" problem means that one must always settle for some non-optimal combination of data signal jitter and resolution, adjacent track crosstalk, and TES. To illustrate, **Figure 8** shows signal amplitude and jitter as a function of focus offset for data from an HF pattern (highest density) and an LF pattern (isolated round marks). The head had no astigmatism, the VB of the media was approximately 450×10^{-6} , and since the data were all taken on track with no tracking offset, feedthrough did not affect the results. In comparing the signal amplitudes, notice the large focus offset between maximum amplitudes [Figures 8(a) and 8(b)]. Adjusting for maximum HF amplitude causes a loss of LF amplitude. Also compare the jitters as a function of defocus. With the adjacent tracks erased, minimum jitter occurs at the same focus condition for both LF and HF jitter. (This alignment persists with both one and two adjacent tracks recorded.) As first one adjacent track and then both are written, the optimal focus point moves toward optimal LF amplitude. These results are consistent with the effects of astigmatism. With no data written in the adjacent tracks, minimum jitter occurs when the optical spot size is a minimum along the track. The fact that this makes the spot shape elliptical is of little consequence, because little additional noise is picked up. In the presence of written adjacent tracks, the effects of coherent noise pickup become significant. The optimum focus then shifts to a point with less energy in the adjacent track, but at the cost of poorer on-track performance. The point of best write occurred at the focus offset for maximum LF signal.

It would be possible to compensate a given level of substrate-induced astigmatism in the optical head in an optical disk drive. But today's international standards for optical disk substrate materials allow a wide range of material optical properties, so the head compensation approach is somewhat impractical. It is more direct to

deal with disk birefringence at its source by controlling the level of both LB and VB in the disk itself. If the range of disk substrate materials allowed were narrowly limited, it might be sufficient to simply control the level of variability of VB around some convenient nominal level. However, current specifications allow materials ranging from glass to polymers, and their associated values of VB cover the range from approximately zero to 800×10^{-6} . **Figure 9** shows data relating the measured amount of VB to calibrated focus offset. The data suggest a monotonic relationship, with some upward curvature. This behavior would imply the need to limit the VB as well as its variability. The surest way to accomplish this is to drive the allowed value of VB toward zero. This suggests eventually changing from polycarbonate to alternate materials.

Another troublesome manifestation of optical anisotropy in molded plastics arises from its relation to material stress. Stresses imparted in disk injection molding and assembly processes can cause LB variability. One can imagine "global" and "local" stress phenomena in disk fabrication. For example, the global variety might refer to stresses arising from the final disk assembly operation, and the resultant birefringence effects would span many tracks. A more troubling possibility would be the induction of spatially varying "local birefringence" due to the molding of topographical features on the substrate surface (tracking grooves and formatting information—control tracks, sector headers, ROM data, etc.). Variability on such a small spatial scale would be virtually impossible to compensate in any pragmatic way. Practically speaking, global and local birefringence must be controlled through material property control (stress coefficient of birefringence) and the injection molding process.

In summary, because of the various optical beam degradations caused by disk substrate birefringence, it is necessary to control the level of both LB and VB allowed in disks. The limiting values of LB and VB chosen should be related to their allowable impact on drive performance. The resulting specifications on LB and VB in turn determine possible choices of substrate material and disk processing conditions.

Modeling and design of thin films of MO media

This section considers optical, thermal, and magnetic aspects of thermomagnetic recording and MO readout when a focused light beam interacts with a multilayer stack of thin films comprising an MO disk. Representative thin-film stacks of greatest interest are shown in Figure 1(c) and **Figure 10**. Figures 10(a) and 1(c) are of interest in illustrating optical and MO effects; Figures 1(c) and 10(b) are perhaps more interesting from the viewpoint of heat transfer, while Figure 10(b) represents a very

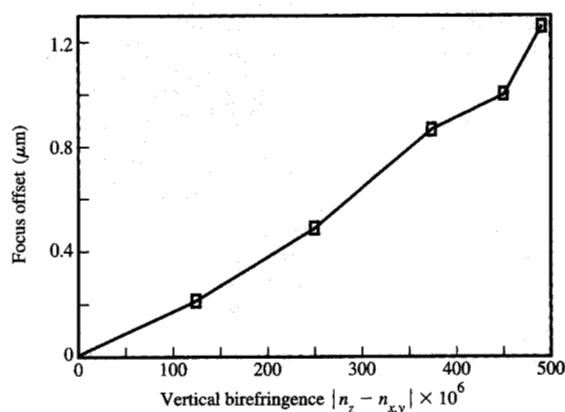


Figure 9

Focus offset (displacement between optimal focus positions for various signals of interest) as a function of average bulk substrate vertical birefringence.

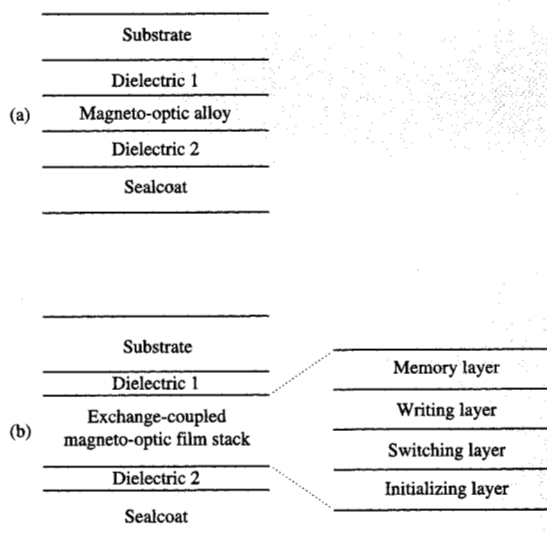


Figure 10

Additional rewritable MO disk thin-film structures: (a) A standard "trilayer" magneto-optic film stack. (b) A typical exchange-coupled multi-magnetic-layer film stack for laser-modulated direct overwriting. The thickness scales shown here are comparable to those in Figure 1(c).

complex magnetic system used in achieving a direct overwriting function. We discuss some examples of each of these coexisting physical issues.

• *Optical and thermal*

The literature is replete with the optical and MO analyses of multilayer thin-film systems, both for optical data storage and other applications [8]. A rather thorough understanding of the trade-offs and performance optimization available in data readout from film stacks (ignoring heat conduction response) incorporating MO layers has been developed on the basis of classical electromagnetic theory coupled with a phenomenological picture of magneto-optic effects. Not usually addressed are two additional requirements of the utmost practical importance in the design of film stacks for MO media:

- The film stack design should contribute to optimum SNR performance of the full optical disk drive system (not solely the disk).
- Both *optical and thermal* design of the film stack must be carried out concurrently, since optical interrogation and stack heating always occur simultaneously and cannot be separated.

It is fairly easy to arrive at a film stack geometry that optimizes a single disk response parameter, such as Kerr signal, or s-p phase shift, or perhaps SNR. A more important practical requirement is to jointly optimize a host of media design parameters to yield the best composite recording performance. These might include

- Full-system SNR.
- Reflectance (the fraction of incident light reflected from the surface) within a certain range.
- Disk film stack phase shift from the Kerr effect matched to compensate the disk substrate and drive optics.
- Media thermal sensitivity and heat flow characteristics matched to the drive laser, channel, and recording code/density.

Recall from the previous section that substrate birefringence must be tailored according to similar full-system considerations. We view the optical design of thin films in this same global context.

Because the OD must support writing, erasing, and reading, we must consider *all* of the optical and thermal design issues of importance, including

- Coupling (conversion) efficiency of focused radiation to heat during write/erase.
- Elimination of excessive media thermal intersymbol interference (ISI) along a track and thermal crosstalk between adjacent tracks during write/erase.
- Design optimization for readout performance (the native Kerr effect of most MO recording materials is weak).

Joint optical and thermal modeling requires that thought be given to strategy and method, because the computational effort in carrying out a thermal calculation is perhaps ten times greater than for an optical/MO calculation.

Before summarizing some typical findings of optical, MO, and thermal simulations aimed at optimizing film stack designs, we present the essential elements of the optical/MO and thermal models used. More details are available in References [2, 9, 10]. The optical/MO model is a standard thin-film multilayer optical model analysis [8] which considers only normally incident rays. MO response is easily included by generalizing the optical properties of the storage layer to include its refractive indices for response to right- and left-hand circularly polarized light rays. A postprocessor for the optical/MO model is a module that computes the expected MO data signal level and the various system noises as functions of the optical/MO response parameters, including reflectance (R), Kerr rotation (Θ_K), Kerr ellipticity (ϵ_K), etc. This SNR model is semi-empirical in the sense that the noise terms with their appropriate functional dependences on optical/MO parameters were provided coefficient weightings corresponding to experimental noise characterization from a test stand. The combined optical/MO model and SNR model can be run in search or mapping mode, meaning that a scan of film stack thicknesses (τ) can be made to reveal the optimally performing structure or a map of the response space. Various performance figures of merit have been used to study composite, weighted objective functions to search for optimal designs.

Figure 11 shows typical contour maps of MO quadrilayer signal and SNR performance for cases of $\tau_{MO} = 10$ nm and $\tau_{MO} = 20$ nm. The x- and y-axes represent variation in the thickness of the D2 and D1 dielectric layers, respectively [see Figure 1(c)]. The range of variation of τ_{D1} and τ_{D2} was chosen to be about 30% larger than one optical period, so that the periodicities in the optical and MO responses are evident. The MO readout signal is proportional to $R \sin 2\Theta_K \cos 2\epsilon_K$, so these plots reflect composite optical/MO effects. Exact periodicity is absent because the refractive index of the dielectric film has been chosen as complex, making the material weakly absorptive. As the dielectric material thickens, the signal and SNR performance degrade.

We note that the 20-nm MO film quadrilayer performs slightly better than the 10-nm film. Quadrilayer performance peaks near 20 nm, rising from zero signal at zero thickness and falling off for MO films much thicker than 20 nm, as the quadrilayer becomes indistinguishable from a trilayer structure in which the MO film is opaque, or nearly so. A partially transmissive MO layer allows an optimally tuned quadrilayer stack to act as an optical

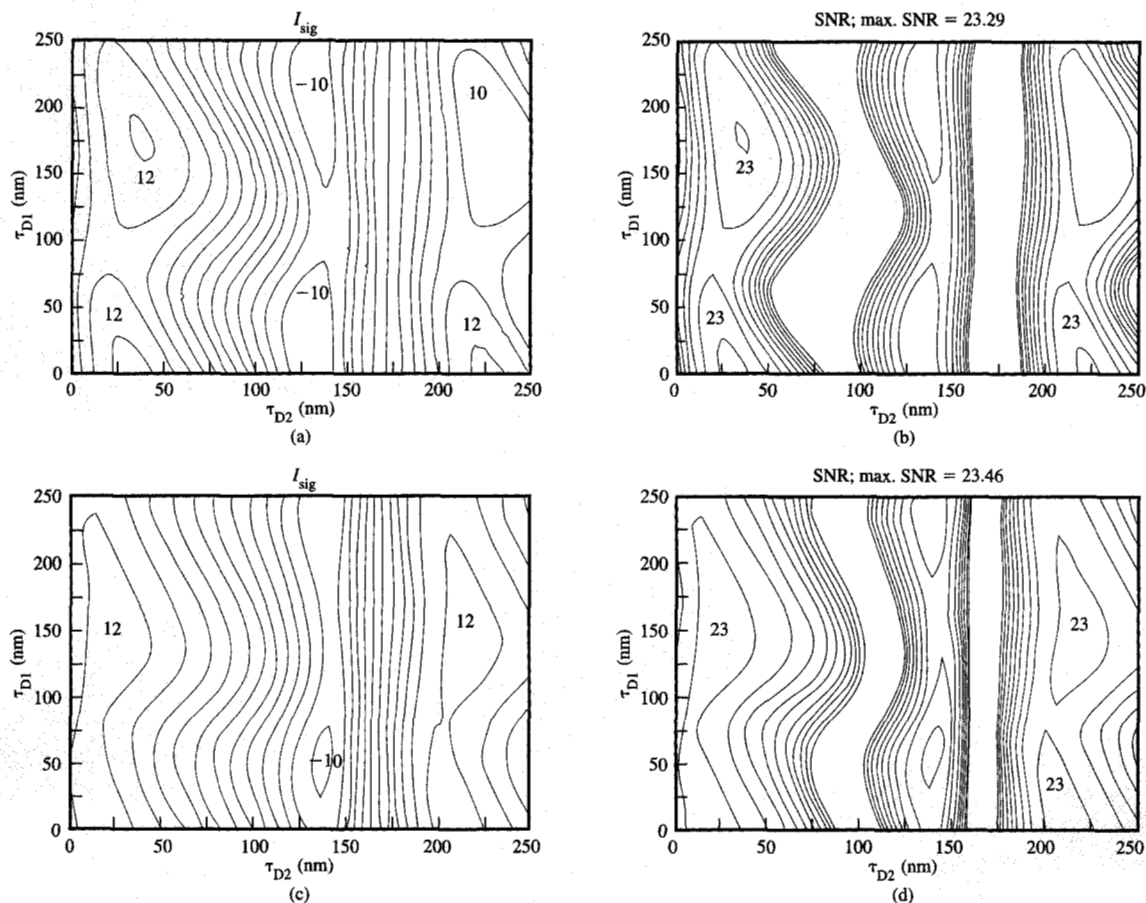


Figure 11

Contours of the MO signal and SNR response for quadrilayer MO stacks as a function of the thickness of the two dielectric films surrounding the MO film, as in Figure 1(c). Values of $\lambda = 780$ nm and $P_{read} = 2$ mW have been used with $n_{D1,D2} = 2.025 - j0.01$; the reflector thickness is 50 nm. (a) and (b) are for a stack with $\tau_{MO} = 10$ nm. The signal contours increment in steps of 2 (arbitrary units) between -10 and 12, while SNR increments in steps of 1 dB between 14 and 23 dB. The SNR contour corresponding to the -10 signal zone is 22 dB. (c) and (d) are for a stack with $\tau_{MO} = 20$ nm and the same contour levels as in (a) and (b), respectively.

resonance cavity. The dielectric thicknesses may be chosen to select optimal phasing of multiply reflected and transmitted rays to build up a peak MO rotation by a combination of the reflective Kerr and transmissive Faraday effects. The reflector layer acts optically as a back mirror. Because the MO signal varies bilinearly with disk reflectance and Kerr rotation, and because R and Θ_K tend to vary approximately inversely, a peak signal solution represents a trade-off between R and Θ_K , using intermediate values of both. The signal is bipolar because of the bipolarity of Θ_K .

Once a desirable region of design space has been identified from the optical/MO/SNR model, thermal analysis is used to find a desirable joint design. The

thermal model we use combines a thermal impulse response from a three-dimensional finite-element solution of the heat conduction problem for the full thin-film structure on the substrate receiving focused light beam irradiation. An axially symmetric impulse solution is transferred to a superposition program that carries out a Green's-function calculation of the full thermal field solution for a moving heating beam whose power is modulated in an arbitrary manner. The result is the time evolution of the three-dimensional temperature $T(t, x, y, z)$.

One approach that has been successful for conventional trilayer and quadrilayer MO structures is to do an initial mapping of the optical/MO response surfaces (several

hundred samples) as reasonable ranges of film thickness are considered [9]. From these maps, small subregions of the best system readout performance can be identified. Next, tests of the thermal response of the system can be made at a few points within the best optical/MO subregions. If satisfactory thermal response is found at this stage, the joint optimization process ends. While this approach has not guaranteed identification of true optimal joint performance, it does reach a quite acceptable solution quickly. The missing component is, of course, a complete mapping of thermal response, which is prohibitively expensive. As a practical matter, for quadrilayer enhanced readout structures, the region of best optical/MO performance is quite restricted ($10 \text{ nm} < \tau_{\text{MO}} < 30 \text{ nm}$). Furthermore, the trend of thermal behavior is quite obvious as τ_{D2} and τ_{Ref} are varied. This simplifies the search for optimal joint optical and thermal performance.

• Magnetic

The magnetic storage layer(s) used today for rewritable optical storage are amorphous rare-earth-transition-metal (RETM) alloys [11]. These materials exhibit strong perpendicular anisotropy in appropriate composition ranges, and, as ferrimagnetic systems, offer readily adjustable coercivity $H_c(T)$ and magnetization $M_s(T)$ behavior through selection of the Curie and compensation temperatures via composition variation. With the usual elemental components (RE = Tb, Gd, Dy; TM = Fe, Co), satisfactory levels of low-noise magneto-optic response are available in the near-infrared and long-wavelength visible portions of the spectrum matching present-day diode laser sources.

The basic magnetic behavior of the RETM film system is well described by a small collection of models:

- Mean-field (MF) model—gives average, temperature-dependent magnetic properties of RETM alloys—magnetic anisotropy, magnetization, exchange coefficient, domain wall energy density, and coercivity [12].
- Bubble model of cylindrical domain stability [13]—based on studies of magnetic bubbles.
- Micromagnetics model of thermomagnetic domain switching [14]—numerical simulation of interacting cells.
- Nanomagnetism model of full magnetization dynamics and origins of coercivity [15].
- Exchange coupled layer (ECL) models (analytic, numeric) that include interfacial exchange and domain walls [16].

All of these models have had thermal analysis coupled into them to some degree; therefore, taken together, they can account for the first-order magnetic properties of RETM alloys and the phenomena of thermomagnetic

writing. Each of the models deals with the magnetism of the perpendicular anisotropy film in some degree of approximation, and to a large extent the models are complementary, each dealing with a particular aspect or level of detail of the problem.

The MF model gives the temperature dependence of average alloy magnetic properties. As such, it provides useful input to many of the subsequent recording models. The bubble model treats the energetics of an idealized cylindrical region of reversed magnetization (a magnetic domain), including the phenomenological influence of the domain wall. To the extent that wall curvature effects can be ignored, the bubble model provides a “balance of forces” picture of domain stability (indicating growth and collapse tendencies).

The micromagnetics model extends the bubble model by subdividing the film into a mosaic of interacting cells (tiles), thus allowing for departures from circular symmetry and enabling moving write beam analysis. All of the magnetic models are based on energy-minimization principles. Three features of the micromagnetics model energetics are notable:

- The assignment of domain wall energy density to the cell interfaces tends to overemphasize this energy contribution.
- The calculation of magnetostatic energy should (in principle) account for all $N(N - 1)/2$ pairwise interactions between N cells, and is therefore computationally intensive. In practice, one can usually truncate the long-range magnetostatic summation beyond some radial distance from a reference cell with tolerable error.
- Coercivity is a by-product of the physics installed in the model, not an *ad hoc* input, as in the bubble model. This is a more intellectually satisfying situation in that the input physics determines the full range of system characteristics without the need to artificially append a particular aspect.

Also, the strong temperature dependence of RETM magnetic properties usually means that magnetization reversal occurs for all regions in which T exceeds some critical temperature (usually in the neighborhood of T_c), so a simple thermal model that ignores magnetism can estimate written patterns by mapping the position of the cumulative time isotherm $T = T_{\text{write}}$. However, a simplified thermal “write model” (without magnetism) is unable to account for domain wall irregularity, a primary source of signal jitter (noise) experienced in recording on these materials. The micromagnetics model has been used to evaluate signal jitter due to MO media and other sources [17].

Figure 12 shows typical results from the micromagnetics thermomagnetic write model. Figure 12(a) illustrates "mark bloom" for a simple rectangular write pulse, while the particular distributions used for the random assignment of cell properties have yielded considerable domain wall jaggedness. Mark bloom is overall mark enlargement caused by heat buildup in the writing process, often manifesting itself as a teardrop-shaped mark, with the trailing edge becoming enlarged relative to the leading edge. Figure 12(b) shows that blooming can be alleviated by applying laser pulse power compensation—power pre-emphasis when beginning writing on "cold" media is beneficial [2], especially Chapter 7). Notice how the additional boost of applied power at the start of the writing pulse fills out the beginning edge of the mark and makes the leading-edge radius of curvature more similar to the trailing edge. Further tuning of the power profile could make the mark in Figure 12(b) a symmetric racetrack shape. Figure 12(c) illustrates an incomplete domain erasure with insufficient erase power.

Perhaps the ultimate treatment of magnetization dynamics and reversal in RETM alloys is found in a nanomagnetics model which provides solutions of the Landau-Lifshitz-Gilbert (LLG) equation on a dense mesh of lattice points [15]. A massively parallel computing system has supported temporal solutions on a 256×256 mesh with 1-nm lattice spacing. The resulting $0.25\text{-}\mu\text{m}$ -square solution region is sufficient to study nanometer-scale details of domain wall evolution and internal structure, but is too small for micrometer-scale thermomagnetic writing studies. Because the time steps are typically of the order of picoseconds, a full magnetization reversal solution spans at most a few nanoseconds. The nanomagnetics model fills in the detailed magnetic behavior of RETM materials (for example, full internal structure of domain walls), but with spatial and temporal resolution too high for practical recording studies such as those provided by the micromagnetics model. One key contribution of the nanomagnetics model has been to provide insight into origins of coercivity in amorphous RETM alloys. The model shows that a plausible account of the variation in $H_c(T)$ known for these materials is possible by postulating the existence of a film-filling mosaic of (approximately) 10-nm-diameter random "patches" of fairly uniform magnetic properties. The simulated implications of this structure (coercivity predictions; domain growth under applied field) are in excellent accord with observations. The reality of the patches has recently been inferred from independent experimental results² [18]. Further, the physical existence of such patches in film preparation is

² M. Madison, IBM San Jose; M. Mansuripur, University of Arizona; and B. Finkelstein, Tucson, AZ; private communications, 1993.

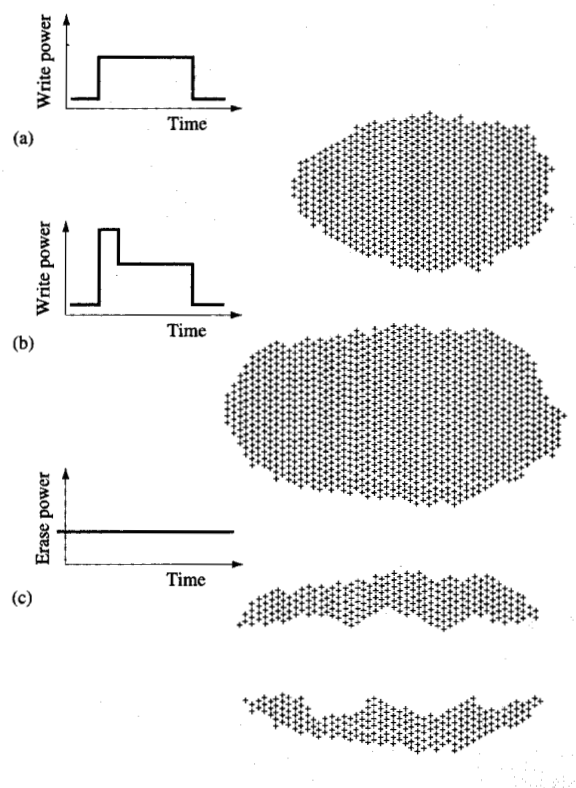


Figure 12

Result of thermomagnetic writing with a micromagnetics model. Different laser power pulsing schemes are illustrated. In (a), a simple rectangular pulse results in mark "blooming"; (b) shows how simple power compensation can alleviate severe blooming—note that the leading and trailing edge curvatures are more similar; (c) illustrates incomplete mark erasure due to application of insufficient erase laser power.

consistent with the morphological development known to occur in sputtered or evaporated thin films.

● Exchange-coupled systems (DOW, MSR)

The last magnetic models we discuss help us to understand the behavior of exchange-coupled-layer (ECL) film stacks. These multiple-magnetic-layer structures exhibit ferromagnetic or antiferromagnetic exchange interactions between adjacent layers with a wide possible range of strengths. These stacks can display quite varied properties for performing sophisticated operations of direct overwrite (DOW), magnetic superresolution (MSR), or enhanced MO readout in laser-modulated thermomagnetic recording. (A primary attraction of the use of ECLs for DOW is that the overwriting can be effected with simple modulation of laser writing power, and the complication of bias magnetic field modulation

can be avoided.) Analytic models of ECL behavior are quite simple accounts of magnetic energy minimization with interfacial domain wall (exchange) energy included. This typically leads to algebraic relations that define layer switching and stability criteria [19]. A recent numeric model of ECLs [20] was based on a solution of the LLG equation in a plane perpendicular to the film plane. An unusual sinusoidal variation in film properties was hypothesized to give rise to coercivity. A true three-dimensional lattice-numeric solution of the LLG equation is probably too expensive for routine use on today's processors. The analytic model for ECLs appears to be entirely adequate for most engineering design work at present. The major design challenges are achieving adequate laser power margins for all recording functions—direct overwrite (the simultaneous achievement of adequate SNR for the new data and erasure of the old data), MSR, and repeated readout without read cycling degradation.

MSR is a clever means [21] of exploiting the natural temperature gradients under a moving focused laser read beam to provide MO readout of a memory layer through thermal apertures in an ECL. Kaneko [21] shows illustrations of the aperturing with different combinations of ECLs. The aperture geometry is defined by the specified temperature dependence of the exchange couplings between layers. While MSR enhances the readout resolution of a diffraction-limited, focused spot, it unfortunately provides no advantage in writing smaller features with conventional laser-modulated writing. The most effective method of thermomagnetically writing very high-medium linear density information is with magnetic field modulation (MFM), a method that provides DOW and encoding in the length of domains (as in pulse-width-modulation recording) as by-products. MFM thermomagnetic recording amounts to thermally assisted magnetic recording. Unfortunately, it requires rapid modulation of a magnetic bias field, but the usual optical recording configuration demands that the bias field source be well separated from the writing location on the disk, and a distant source is incompatible with rapid modulation [22]. Thus, despite its many attractive attributes, MFM DOW appears to be destined either to be slow or to dispense with a traditional advantage of optical recording, avoidance of an intimate head-disk interface that demands extreme system cleanliness (freedom from particulate debris or contamination). The degree of cleanliness associated with a flying magnetic head could be incompatible with the use of interchangeable media.

To summarize the situation with ECL technology, the adoption of this media structure forces choices and compromises between modes of DOW function, and also among optimization of writing, reading, and data rate

performance. This has possible implications for the design complexity of both media and the entire optical disk drive.

Recording performance testing of MO media

For rewritable MO data storage media, it is important to test three functions—writing, reading, and erasing ([2], Chapters 7, 10, and 11). These functions are clearly interconnected, and the tests must therefore be interrelated. It should be pointed out that WORM media support no erase function, and that implementing a write function without the availability of erase is challenging. For example, an operation that is natural for rewritable media such as write optimization through power calibration may be available only in a very abbreviated form for WORM media—"practice" writing consumes WORM media.

A fundamental writing test for optical recording involves assessment of readback signal amplitude or written mark length (as perceived by reading) versus write power. Mark length assessment is the usual mode of testing for pulse-width-modulation (PWM) recording, since digital information is encoded in the length of written marks (and the intervening spaces). The key information to be gained by studying signal amplitude or mark length versus write power includes

- Threshold writing power, a measure of media writing sensitivity.
- Optimum writing power.
- Possibly an estimate of write power margin, the power range over which acceptable writing can be performed.

Writing tests are crucial for determining the sensitivity of the writing process to variation in drive parameters such as write power, bias field, and disk temperature. One can assess the sensitivity of signal amplitude or written mark length to these variables. The sensitivity of media to repeated write/erase cycles can be probed by monitoring amplitude or mark length shifts on a track repeatedly recorded under fixed conditions (sometimes called "sensitivity shift with time," or SST). Such a test gauges the reversibility of a mark recording process under conditions of thermal stress—for example, the thermomagnetic recording cycle on MO media. The above sensitivity tests monitor shifts of the mean signal amplitude or mean mark length as some recording condition is varied. Thus, they cause systematic offsets of recording performance rather than stochastic variation. MO materials are affected by write/erase cycling effects to a lesser degree than are phase-change media, with typically ten times or more cycles possible for a given parameter offset with MO media than with phase-change media.

Next we turn to a different class of variations that can be probed by writing tests. Medium uniformity can be determined by studying amplitude or mark length variability over the disk surface under fixed writing conditions (power, bias, speed, temperature). Medium nonuniformity is characterized by media property variation with a correlation length much greater than a single recorded feature size. Medium variation such as this can be compensated by an adaptive electronic channel in an optical drive, since the variational frequency is well below the data frequencies. At the other extreme in variational frequency (or very short correlation distance, less than a recorded feature size) is a phenomenon causing medium "bit jitter," a stochastic variation contributing to noise in the recording system. Jitter manifests itself as random variations in signal peak amplitude or peak location, or in PWM recording as random variation in mark edge placement. The nonrepeatability of mark edge placement in MO recording is physically related to two classes of effects:

1. *System contributions* Fluctuations in the condition and position of the writing laser spot as it translates down the track because of laser power variation, write driver pulse timing variation and noise, spot focus servo misregistration, spot tracking servo misregistration; variations in the applied magnetic bias field; variations in the ambient temperature inside the optical drive.
2. *Media contributions* An inherent inability to repeatedly place a thermomagnetically recorded domain wall using micron-size laser spot heating when the nanomagnetic processes governing wall dynamics are determined on a length scale of order 10 nm variation in storage material composition, as well as physical and chemical properties, contributes on all length scales to this mark placement variance.

Jitter is measured by determining a feature-to-feature timing distribution with a time interval analyzer. The features are either signal pulse peak locations (pulse position modulation—PPM) or mark edges (PWM). Nonmedia sources of jitter (system noise—shot, electronic, laser) can be isolated by gating on a single feature pair to reveal a repetitive interval distribution, and then removing the system component from total measured jitter by quadrature subtraction.

Jitter is a time-domain manifestation of noise in the recording system. An alternative view is provided by spectral analysis of the recording channel electronic signals, yielding a frequency domain picture. With the frequency domain representation, it is customary to quote various SNR metrics. The signal level can be measured as a peak signal amplitude in a time-domain representation, or as the amplitude or power of a particular signal

harmonic from a spectrum analyzer. The noise amplitude or power is always measured with spectrum analysis, and may be the integrated broad-band noise power, or it may be the narrow-band noise power in a frequency "slot" around the signal or carrier harmonic of interest. A ratio of carrier harmonic to slot noise level is called "carrier-to-noise ratio" (CNR). CNR, although popular in the standards and tester communities, is at best a very rough comparative indicator of media or system performance, since it takes into account the noise at essentially one frequency only. Under certain simplifying assumptions, jitter and SNR can be interrelated; for sinusoidal signals, jitter is essentially signal noise rms amplitude divided by tone signal slope at the detection point.

Medium noise can be quite easily divided into at least two components. "Erase noise" is the media component of measured jitter detected when reading a completely erased track. After a signal pattern is written, a remeasure of medium noise will show a high value, the additional noise arising from the variation (from mark to mark) in the domain walls forming the mark boundary. This additional medium noise component is dubbed "writing noise" (jitter). The ultimate sources of the noise consisting of these two medium noise components are specific to the storage material system in use³. For example, for the common RE-TM alloys used in MO recording, there are noise contributions arising from reflectance and Kerr rotation variation due to material inhomogeneity on a submicron scale, as well as beam depolarization which occurs during light interaction with the disk films and substrate topography.

A final writing test in MO recording assesses thermal interference between adjacent written features. Because of the heat conduction properties of the substrate and thin-film materials in the disk, closely spaced writing events can interact thermally, perturbing the intended placement of magnetic domain centers or edges. **Figure 13** shows a thermal simulation of the writing of adjacent PPM domains and illustrates how the writing of the first mark preheats the disk material where the second mark is to be written. Consequently, the second mark is larger than the first. The locations of the PPM readback peaks are shifted toward one another because of both optical and thermal ISI. The optical component arises simply because of the finite size of the written domains and the reading spot, while the thermal component actually displaces the center of the second written mark toward the center of the first mark because of the shape of the decaying thermal field after the first writing pulse is turned off. One can devise timing analysis tests of worst-case thermal interaction patterns to assess the level of thermal ISI in both PPM and PWM recording.

³ See the chapter on noise by B. Finkelstein in [2].

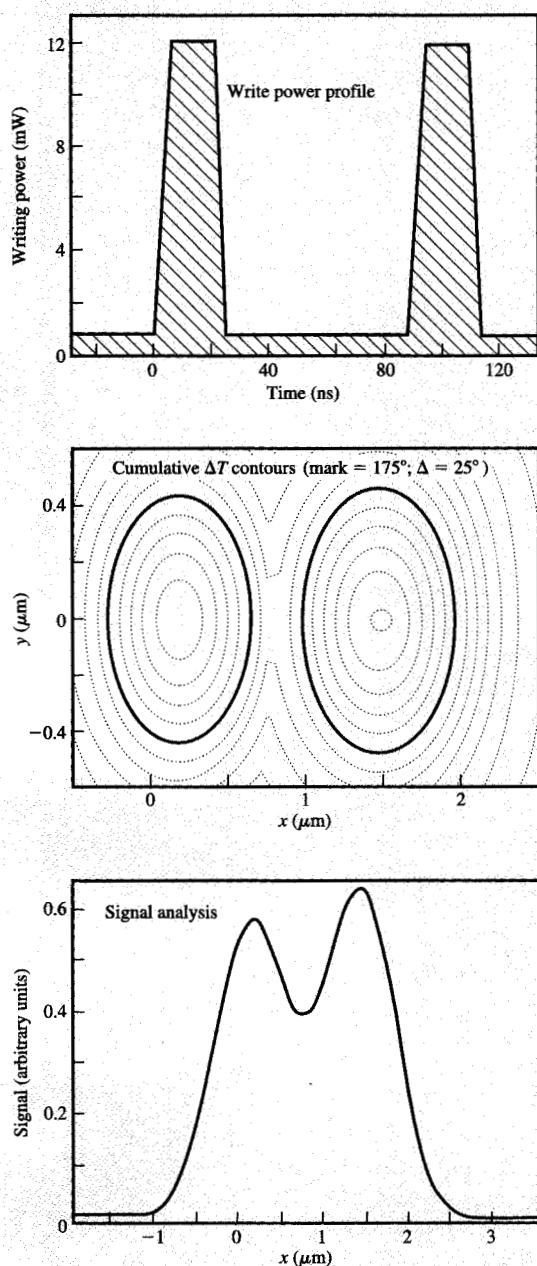


Figure 13

Result of a thermomagnetic writing and readback simulation illustrating thermal interaction of two closely written magnetic domains. Preheating in writing the first mark results in an enlarged second mark and a corresponding effect on readback signal.

MO erasure testing can be done in a variety of ways. A straightforward test is to plot the residual readback signal level (usually sensed with a spectrum analyzer) from an

optimally written track as a function of the erase power or erase magnetic field. Critical points on the monotonically decreasing plot include the onset of on-track erasure and the completion of erasure (when the residual signal or carrier level merges into the system noise floor). Often, one is interested in determining adjacent track erasure effects. Here, one might monitor the readback signal on optimally written track n while the erase power applied on optimally written track $n + 1$ is varied. More sensitive stress tests could involve monitoring jitter degradation on track n while track $n + 1$ is erased. Worst-case adjacent track erasure might involve monitoring jitter on weakly written track n while erasing strongly written track $n + 1$. Tracking misregistration could be added as a further worst-case stress.

Erase-power calibration can be performed by adjusting erase power to some optimal intermediate position between the achievement of complete on-track erasure and avoidance of adjacent track readback degradation. Erasure quality may be somewhat dependent on whether the thermal input for the thermomagnetic removal of a written pattern is provided by application of continuous wave (CW) laser power, or by pulsed power input. When integrated energy output of the laser (possibly affecting laser lifetime) or input to the disk (possibly affecting media SST) are issues, the mode of laser excitation may be important. Pulsed power input is usually more energy-efficient than CW irradiation ([2], Chapter 7).

Readback tests are obviously integrated into all of the above writing and erasure tests. However, there exist specific readback stress tests such as read stability testing. In this test, readback amplitude or jitter is monitored while read power is stepped upward with an erasure magnetic field applied. (Bias fields are commonly "on" during readback in MO drive systems, even ones utilizing electromagnetics—switching times are too slow to guarantee an "off" condition during reading after writing or erasure.) The purpose of this measurement is to determine the maximum usable readback power without causing damage to written data, since readback performance generally improves with read power up to the onset of unwanted degradation of recorded information.

A popular high-level performance test applied to media is error-rate testing. Error testing usually involves both media issues and drive channel and hardware issues. For this reason, it is probably not a "clean" media test in all cases. A more basic measurement that detects media "defects" is perhaps closer to a true media test. In practice, optical drive error rates are usually dominated by media defect perturbations to recording signals, rather than by random noise effects as measured by SNR or jitter. This balance is the result of intentional design approaches which are based on a philosophy that a system should be performance-limited by a base intrinsic level of

medium defects rather than noise-error-limited. In any case, from a media perspective, it is important to understand any changes that media "defects" undergo during media aging or exposure to a range of environments.

Mechanical testing of disk and cartridge

It is perhaps easy to overlook the stringent engineering requirements associated with the physical carrier of the user data and its housing, namely the disk substrate and the surrounding protective cartridge. But the simple truth is that the integrity of data storage media is only as good as the mechanical delivery system that supports and guards the thin films where the information resides. The physical characteristics of the disk and cartridge systems for optical data storage media—whether read-only, write-once, or rewritable—are very carefully specified, often in international standards [5]. Significant portions of these standards are devoted to detailed layout of the physical dimensions of the disk and cartridge, as well as providing thorough descriptions of the function and mechanical performance of each component. Such care is necessary to ensure media interchangeability and long-term reliability under wide ranges of environmental conditions and handling.

A primary purpose for the control of disk mechanical properties is to ensure the workability of the focusing and tracking servo control systems in the optical disk drive. These systems must hold the axial focal point position of the laser beam to within $\pm 1.0 \mu\text{m}$ of the plane of the storage layer (focus misregistration—FMR), and hold the lateral position of the spot center (disk radial direction) to within approximately $\pm 0.1 \mu\text{m}$ of the track centerline (track misregistration—TMR) while the disk substrate moves tens to hundreds of microns as the disk rotates under the largely stationary optical head (see "runout," described below). Without exception, these servo systems have distinct limitations on the physical displacements through which they can drive a payload to follow disk motions and the rate at which these excursions can be achieved.

Testing of disk "mechanicals" or "physicals" covers the measurement on a dynamic test stand or spin stand of several performance attributes. Disk circularity or concentricity is controlled by specified limits on radial runout of the tracking grooves relative to the disk center of rotation, which is established by chucking the disk on a motor spindle. Optical data disks are supplied almost exclusively with a permanent hub affixed to the disk to define an accurate and repeatable axis of rotation relative to the nearly circular spiral tracking groove. Radial runout is the maximum-to-minimum radial excursion of a data track during one disk revolution. Associated with this displacement is a limit on the radial acceleration

experienced by an object locked to this groove with runout. The radial acceleration is usually limited within a specified frequency band related to the disk rotation rate (and its harmonics) during use.

Mechanical displacements of the disk surface normal to the average disk plane are controlled by limitations on the axial runout, the axial acceleration, and the disk tilt. Axial runout is the peak-to-peak vertical displacement of the disk surface during disk rotation, while axial deflection is the absolute vertical displacement of a point on the disk surface from an imaginary reference plane. Axial acceleration is characterized in a frequency band in a way similar to radial acceleration. Tilt is local surface slope in both the radial and tangential (to the track) directions. Clearly, these mechanical properties are related to non-flatness of optical disks. Also, there can exist axial resonances excited by the drive spindle motor vibrations, and characteristic oscillation modes may be measured. These resonance modes have characteristic "eigenfrequencies" determined by the structural properties of the disk assembly. Although disk resonance is widely recognized as a mechanical performance characteristic that can have important consequences for the operation of the complete disk drive system, it has not been customary to control this property via specification in the standards to date. As higher RPM operation at greater data densities is practiced in the future, it is expected that it will become necessary to bound disk resonances.

The disk mechanicals discussed thus far are usually measured under ambient conditions, but interchangeable optical media must be guaranteed to function over a range of environments, typically covering 5–50°C and 3–85% RH with a maximum dew point of 29°C. Some means of testing is usually undertaken to ensure robustness of operation over this range of conditions. It usually entails interchangeability testing of media in drives operated in environmental chambers representing the "corners" of the environmental ranges specified. Besides, an accelerated aging test of disks at "stress" environmental conditions may be used to provide an estimate of expected disk life at virtually any allowed operating or storage condition. Because the expected failure modes of an optical disk—a composite, assembled system of subcomponents—may be complex, the projection of expected disk mechanical life is not as straightforward as life estimates for disk thin films that may be subject to a single chemical degradation or corrosion process.

Mechanical testing of an optical disk cartridge usually involves determining its robustness during load-unload cycling into an optical drive. An additional test appropriate for optical media cartridges used in optical "jukeboxes" or optical library autochangers is for ruggedness against mechanical stresses associated with multiple cartridge fetches and handling by robotics in

transport between cartridge storage shelves and the disk drive or player. One specifies "mean swaps between failure" as a measure of cartridge robustness in virtually any conceivable optical library application.

Film life testing and quality assurance

IBM warrants its data storage media products against defects over their lifetime when the media are used under specified operating and storage conditions. This warranty is established by rigorous testing of optical disks involving accelerated aging in environmental chambers and statistical projection to establish credible confidence intervals. A typical reliability claim asserts that "97.5% of media is expected to exceed N years life in operation at 30°C and 80% RH with 95% confidence."

This assurance is based on the testing of media recording performance parameters in an array of different stress environmental conditions (called "cells")—for example, 80°C and 85% RH. A statistically significant number of samples are placed in each cell. Performance testing is carried out on optical drives or test stands at pre-established times, for example after 0, 500, 1000, 1500, and 2000 hours elapsed at the cell environment. By logging the evolution of the mean performance at these times at various cell conditions, one can derive aging "acceleration factors" that make possible the projection of expected disk life at any other environment. The premise of the above analysis is that a disk failure mode induced by the stress conditions is understood and is probably a chemical or physical change driven by an activation energy according to a simple empirical law, such as an Arrhenius (temperature dependence only) or Eyring (temperature and humidity dependence) process. A common recording system performance parameter that is measured and seems to conform to the conditions described above is the data bit or byte error rate. Such a parameter is clearly associated with the density and size of "defects" in the disk storage layers, and it is plausible that defect nucleation and growth may be a chemical process driven by temperature and/or humidity factors. The number of sectors spared because of excessive defects are strictly limited, as are defect size and number per error correction code (ECC) interleave.

The quality assurance for the media product is achieved by careful review of several datasets and by analysis of the media manufacturer's provided information on statistical process control (SPC) of his product. The datasets that are reviewed closely include

- Life projection information from disk thin-film and mechanical performance.
- The results of optical drive verification tests run by Drive Integration.

- The manufacturer's own data demonstrating SPC; IBM requires processes to meet $C_{pk} > 1.0$, a metric of process control derived from sampled measurements that ensures adequate yields and process stability. This metric essentially controls the placement of the mean and the magnitude of the variance of a normally distributed process relative to the specification limits. Also, control charts monitoring production processes are reviewed.
- Results of load/unload testing of disk cartridges in the drives.

Future directions

What are the optical media technology directions of the future? We list here some areas in which media improvements are needed and expected for optical data storage to remain a viable technology.

Short-wavelength SNR

Wavelength is a first-order parameter related to areal density, and it will be reduced as rapidly as the availability of low-cost, compact radiation sources permits. Rewritable media that will support adequate SNR performance will be needed. Promising MO candidates in the green and blue regions of the spectrum are Co/X ($X = \text{Pd, Pt}$) multilayers, thin-film garnets, Heusler alloys, and perhaps modified RE-TM alloys. Issues to be settled include media noise minimization, chemical and thermal stability, and low-cost fabrication.

Reduced thermal interaction

Thermal interference among proximate features in thermomagnetic recording must be controlled and minimized to allow increased areal density recording. This is generally achieved by "heat-sinking" the recording layer(s) adequately. The aim is to have axial heat flow dominate lateral flow so that adjacent features are thermally isolated to the greatest degree possible. The price paid for this aspect of control in thermomagnetic recording is relinquishment of recording sensitivity, which puts high demands on laser power.

Direct overwrite and media superresolution

This was summarized in a preceding section. Today, there are two competing paths between laser modulation and MFM forms of DOW, with each offering complementary strengths. A form of DOW with a more complete complement of desirable attributes is needed. MSR is a promising contributor to the general technology development of superresolution, whereby readout resolution is enhanced so that the pressure for short-wavelength sources to support high-density reading is reduced. A drawback of ECL film structures to support laser-modulated DOW and MSR function is that the manufacturing processes to control their production will

have greater complexity than those practiced today. Simultaneous achievement of DOW and MSR in a single film structure is unavailable today.

Better optical substrates

Inexpensive injection-moldable materials with excellent optical properties, especially low birefringence, are needed to succeed polycarbonates. The material should feature good mechanical properties in thinner disks ($t \leq 0.6$ mm); thinner substrates lower sensitivity to birefringence and mechanical tilt problems. Material stiffness and rigidity is important, since disk rotation rates beyond 5000 rpm will be required in the future.

Sample servo

This is often viewed as a means to avoid the drawbacks of today's dedicated servo using tracking grooves which cover 100% of the disk surface. This mixing of data and tracking features creates a situation in which grooves contribute to media noise on readout. Thus, although sampled servo generally imposes a disk real-estate overhead penalty, the trade-off for reduced noise in data zones may be worthwhile.

Servo writing or soft formatting

Servo writing here means that servo or format information is recorded into the medium rather than embossed into the substrate (hard formatting). If soft formatting could be carried out at no additional cost to the user, it could be beneficial for avoidance of difficult dual-level mastering of the preformatted disk substrate; this is especially true at shorter wavelengths and higher densities. Also, soft formatting could be more compatible with bilevel recording (on equally spaced grooves and lands—also called land/groove recording) on a grooved disk.

Media modeling

One would expect future advances in computer processing speed and parallelism to permit development of more ambitious three-dimensional thermomagnetic recording models. Similarly, more widespread use of vector diffraction analysis is anticipated. The routine use of better simulations will probably mean that representations of the detailed interaction of electromagnetic radiation with the optical disk will also become commonplace.

Volumetric storage

The development of low-cost manufacturing techniques for multilayer optical media [23] will provide a spur to reduce the cost per byte of optical solutions. Besides multilayer approaches, other means of achieving three-dimensional recording will continue to be investigated to allow optical storage to keep pace with other forms of data storage for volumetric storage density.

Lower-cost designs

There is great benefit in reducing the cost of data storage, and the cost of media has significant leverage on optical storage system costs. For today's optical media, high cost is in large part due to use of a very robust cartridge of suboptimal mechanical design which is expensive to manufacture. This problem is in principle addressable by engineering means. And higher-volume production of optical storage components will naturally drive prices lower.

Summary

The development and manufacture of high-quality interchangeable data recording media within the constraints of an international standard are reviewed. The key to achieving this goal is to determine those aspects of the design which provide product differentiation, and to fully leverage unique strengths of product development and manufacturing organizations to significantly exceed minimum requirements in those performance areas. We have reviewed several interdisciplinary performance areas that have received particular focus: thin-film optimization, substrate birefringence, groove and format feature design and manufacture, disk and cartridge environmental stability, and disk/cartridge mechanical robustness. An additional opportunity exists to create a superior data storage system by designing the medium to be optimally compatible with the optical drive [10], since the degree of interaction of drive and medium is so great that the isolated design of each separately can never guarantee that the combined system will operate compatibly. The design and testing principles described here will continue to be central to the successful development and manufacture of future optical media incorporating a spectrum of technology extensions.

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