Optical Data Storage
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Optical Data Storage
Phase-Change Media and Recording

By

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1. Introduction

1.1. A brief overview of optical storage systems

Today’s optical storage system stems from a small-scale product developed by Philips and commercially launched in 1978. This system was the result of the Videodisc project that was running at the Philips Research labs in Eindhoven, The Netherlands, through the 1970s. It was pioneering laser-based optical storage and was based on an analogue videodisc. The product never broke the boundaries of its market niche and at its decline the number of contents titles was quite limited. However, with its optical pick-up head, servo electronics, disc mastering principles, and fine mechanics it formed a basis for the optical storage technology employed nowadays. Unlike its predecessor, the next generation system was to revolutionize the world of data storage. The fruits of a close collaboration between Philips and Sony were officially made public in 1979 in the form of a worldwide standard. The first product became commercially available in 1983 under the name of Compact Disc (CD). This was a shiny 12 cm disc carrying about 74 minutes of music in a digital format. Fostered by the fast growth of computer industry a CD for computer applications – Compact Disc Read-Only Memory (CD-ROM) was introduced on the market in 1985. The disc could hold up to 650 megabyte (MB) of data and at 1x disc speed the data transfer rate was 4.3 Megabit per second (Mbps). The CD-ROM makes use of the same physical format as CD-audio but has additional error detection and correction encoding. To meet the ongoing developments in multimedia applications a number of derivatives from the original CD-ROM format have been added to the CD family. Most prominent of them were CD-interactive (CD-I) and video-CD. The CD-I format was defined to enable computer-based digital storage of data, audio, graphics and video. Video-CD is used to store 74 min of combined full-motion video and audio employing MPEG-1 video data compression techniques. Following the success of read-only discs, recordable (CD-R) and rewritable (CD-RW) media completed the family of first-generation optical disc storage in 1984 and 1995, respectively. An important feature of the CD family is the high degree of interchangeability between its different family members. This was one of the main factors promoting the success of the CD optical storage system.

The tremendous technological developments of the late 80s and early 90s have created a great demand and a suitable technological basis for higher data capacities and data rates. In 1996, the second-generation optical storage system – Digital Versatile Disc (DVD) was launched. The disc accommodates 4.7 GB of data on one data layer and its DVD-video format delivers about 2.5 hours of standard-definition (SD) digital video. DVD makes use of the Universal Disc Format (UDF) to enable multimedia applications in both consumer electronics appliances and computer peripherals. It employs MPEG-2 for video compression. At 1x disc speed the system provides a data transfer rate of 11 Mbps. Besides single-layer discs, dual-layer and
double-sided dual-layer configurations have been developed, with 8.5 GB and 17 GB of data capacities, respectively. Within a few years, recordable and rewritable DVD media have appeared on the market. Three mutually incompatible formats - DVD-RAM, DVD-R/RW, and DVD+R/RW, have been standardized by different industry alliances. This incompatibility has led to a so-called format war, which left both the industry players and the consumer on the loosing side. [2], [4]

In June 2002, standardization of a third-generation optical storage system was finalized. The system is called Blu-ray Disc (BD) and was proposed by the Blu-ray Disc Founders, an industrial consortium of 9 leading companies (9C consortium), comprising, among others LG, Samsung, MEI, Sony, Philips, Thomson, Hitachi, TDK, etc. [4], [5] The BD system evolved from the DVR (Digital Video Recording) project running at Philips Research labs and Sony since 1996, this time pioneering blue laser recording. [6] Many of the physical parameters proposed in the DVR system were also adapted to the BD system. The BD system features 25 GB single-layer and 50 GB dual-layer 12 cm discs and a data transfer rate of 36 Mbp/s. Two other data capacities are also described in the format, 23.3 GB and the reserved 27 GB. In contrast to the preceding generations, it was the rewritable disc format (BD-RE) that was described in the first version of the standard. High-definition (HD) video recording is anticipated to be the main driving force from the application side. In 2003, Sony launched the first commercial BD video recorder in Japan. Only BD-RE discs of 23.3 GB data capacity (according to version 1.0 of the BD-RE book) can be used on this recorder. In the mean time, almost all 9C companies started their own drive development activities. A major breakthrough in the proliferation of BD is the successful introduction of the triple-writer optical pick-up unit (OPU) by Philips, ensuring backwards compatibility up to the first generation optical discs. This OPU can actually read and write CD, DVD and BD type of discs. Next to Blu-ray Disc, another third-generation system has been proposed. This system is currently being standardized under the name of HD-DVD (high-definition DVD) and has some major physical differences from BD. A main difference with the BD system is the lower data capacity of 15 GB; a dual-layer version makes 30 GB storage capacity. The future of both systems is unclear as yet. One of the serious issues the optical storage industry has to deal with is copy protection (CP) and digital rights management (DRM) of the data stored on the discs. There is a high probability that success of the upcoming generations of optical storage systems will be determined not only by their storage and retrieval performance but to a large extent by the availability and versatility of CP/DRM solutions.

So, by the time this book is being written two generations of optical storage systems and a plurality of often competing formats have been successfully commercialized. The ‘war’ on the third generation ‘blue’ systems has just started. It seems that the first recordable high-density systems will be utilizing the BD format with a disc capacity of up to 50 GB. Forseen applications are a high-density video recorder and a PC drive. The high-density format allows also for a smaller-form factor drive, such as a Camcorder. The availability of BD-ROM media is of strategic importance for the proliferation of the BD format. But the willingness of leading film studios and content distributors to publish high-definition content in BD-ROM format depends very much on their confidence in the copy protection system of BD-ROM.
1. Introduction

While the market introduction of the third generation optical recording system just started, options for a fourth generation system are already under development in the research labs of several companies. In accordance to the evolutionary increase in data capacity, the near-field system utilizes an increased numerical aperture objective lens to allow for a 100GB single layer data capacity. [7] Also advanced signal processing widens the system margins and enables a single-layer storage capacity of up to 50 GB. [8] Two-dimensional optical storage is a possibility to increase data transfer rates but this system requires a multi-pot readout system. [9] Data capacities of Terabytes are envisioned if the third dimension is explored, so-called volumetric data storage. Recent improvements in recording materials have renewed interest in holographic data storage. [10] Besides the tremendous data capacity, page-based storage involves also a relative high data-transfer rate. Other examples of volumetric data storage are electrochromic media, in which the individual data layers are independently addressable. [11] The University of Arizona explores currently an evolutionary optical storage system based on DNA carriers. [12] Although this system is far away from commercialization, it is based on a very interesting and novel concept.

Nowadays an attractive property portfolio, which includes removeability, robustness, interchangeability, low price, characterizes optical storage media and ‘cool’ look. But what is the physical difference between the different storage generations and how does it work all together? In what follows the principles of optical data storage will be explained on a basic level.

1.2. The basics of optical storage

1.2.1. Optical drive layout

An optical storage system consists of an optical drive and corresponding optical media. The main elements of an optical drive are a semiconductor laser, a set of optical elements to shape and focus the laser beam, a disc driving part, and a signal detection system. In Figure 1, a simplified layout of an optical drive is shown. A light beam generated by the laser propagates through the optical elements of the drive and is focused into a diffraction-limited spot on the disc. Being reflected by the disc, which carries user and service information, the beam is projected onto a set of photo-detectors. The detected signals are subsequently processed by electronics of the drive (not shown in the figure). Among the most important parameters that characterize an optical storage drive are the wavelength ($\lambda$) of the laser and the numerical aperture of the objective lens. The numerical aperture is defined as $\text{NA} = \sin \alpha$, where $\alpha$ is the angle between the optical axis and the marginal ray of the converging beam in air. As will be shown below, these parameters determine the storage density of the system.
1.2.2. Basic principles of optical data storage

The principle of optical data storage and retrieval is explained in Figure 2 in a simplified form. The audio and video signals perceived by users are of analogue nature. It is, however, more convenient and robust to use the digital domain to efficiently store, transmit, and retrieve such signals. For this purpose analogue-to-digital conversion (A/D conversion) is done and additional data bits facilitating error correction (error correction coding, ECC) are added. In its digital form the user data is a binary code represented by a sequence of bits defined as logical “1”s and “0”s.
In optical discs, data is represented by small areas (marks or pits) with optical properties that are different from the optical properties of the surrounding matrix. Marks (pits) and spaces (lands) between them are often referred to as (marking) effects. Typically, an optical medium is designed such that the reflectivity of marks (pits) is lower than the reflectivity of the surrounding matrix at the laser wavelength used. In case of recordable and rewritable media, the written areas (marks) have an intrinsically different reflectivity upon thermal degradation. Amplitude modulation is the main mechanism for readout of data. ROM media are mass-replicated and are in most cases provided with a metallic mirror. Constructive and destructive interference
of the focused laser spot causes modulation, also referred to as phase modula-
tion. To adapt the binary data pattern to the modulation transfer characteristics of the
optical channel, modulation coding is applied. In this process the user data is en-
coded in the length of the effects (the so-called run-length limited, RLL, coding),
which is an integer times a unit-length, the so-called bit-length. To obtain an optimal
match to the spatial frequency characteristics of the optical channel and to achieve
optimum data density a set of lengths is employed. In the case of CD and DVD a set
of run lengths with a minimum of 3 and maximum of 11 channel bits is used. In the
case of BD, the 2-to-8 set is used. More details on encoding and error correction can
be found elsewhere. [13] The marking effects are placed in data tracks, which
typically form a concentric spiral on the disc substrate. To retrieve the information
detection of the marking effects, decoding and subsequent conversion into analogue
signals are done. The optical parameter that is utilized to detect the effects is the
intensity of the laser light reflected by the disc. Upon readout the disc spins and the
focused laser beam scans the data tracks passing over the effects. The reflectivity
level difference between marks and spaces (the optical contrast of the effects) and
the interference in the laser light diffracted by the effects pattern yield intensity
modulation of the reflected laser beam. In order to establish the lengths of the effects
the intensity profile is sliced through and sampled with a predefined frequency,
which is derived from (and, therefore, synchronized with) the rotational frequency of
the disc.
Figure 3. Time (upper plot) and frequency (lower plot) domain signals from single-tone data carriers (I2 refers to a 2T single tone; I5 refers to a 5T single tone).
To give a simple example, modulation profiles of two different single-tone data patterns are plotted in time and frequency domains in Figure 3. An important fact that can be derived from the plots is that in the case of the single-tone carrier with shorter effects (higher frequency) the modulation amplitude is smaller compared to that of the single-tone carrier with longer effects (lower frequency). There are two reasons to explain this. One is the relative area of the effects with respect to the effective laser spot size on the disc. The other is the frequency dependence of the modulation transfer function (MTF), which describes the optical response of a spatially modulated pattern of effects on the disc. In central-aperture-detection systems, MTF decreases monotonously down to zero at a spatial cut-off frequency \( \frac{2\pi}{\lambda} \), where \( \lambda \) is the laser wavelength and \( \lambda \) is the numerical aperture of the system (see Fig. 4). The cut-off frequency limits the maximum information density that can be stored on the disc.

In the frequency domain such single-tone patterns (single-tone data carriers) manifest themselves as peaks at the frequencies (main frequency plus higher-order harmonics) corresponding to the spatial-frequencies of the effects on the disc. Translated into the signal domain, the signal frequencies that can be extracted from an optical disc are smaller than \( \frac{2\nu\lambda}{\lambda} \), where \( \nu \) is the linear velocity of the spinning disc.

![Figure 4. Modulation transfer function of a central-aperture optical channel.](image)

As may be obvious from the above, bit detection is directly related to accurate measurement of the intervals between the slicer crossings in the time domain. Any deviation in lengths of the effects, irregularities in their shape or in local disc reflectivity, cross talk with the neighboring tracks, as well as fluctuations in electronics and laser performance etc. will inevitably alter the intensity modulation profile and
affect detection. In panels (a) and (b) of Figure 5, two intensity modulation profiles obtained for a random sequence of bits are shown. These intensity modulation plots are called the eye-patterns. The eye-pattern in panel (a) corresponds to a perfect case. The eye-pattern in panel (b) corresponds to a case where imperfections are present. As can be seen from the figure the presence of imperfections causes spread in the intensity modulation profiles. When the sources of fluctuations are Gaussian in character, the standard deviation of the Gaussian time distribution is called jitter and is expressed as percentage of the clock-time: \[ \text{jitter} = \frac{\Delta t}{2T} \times 100\% , \] where \( \Delta t \) is the spread at the slicer-level crossings and \( T \) is the time-period. Each mark and space (pit and land) length can be defined as its average length in time domain and jitter in percent of clock-time. An increase in jitter manifests itself in the time-frequency domain as a decrease in the signal strengths, which is characterized by the signal-to-noise ratio (SNR). The relation between jitter and SNR can be expressed as \[ \text{jitter} = \frac{1}{\sqrt{2}} \times 10^{\frac{-\text{SNR}}{20}} \times 100\% . \]

Figure 5. a – eye-pattern calculated for a perfect case; b – eye-pattern with imperfections included; c – measured jitter histogram for a 2T, 8T data pattern; d – magnified section of panel (b).
When analyzing recording media the concept of carrier-to-noise ratio (CNR) has proven to be useful. This CNR is the SNR of a single-tone data carrier written on the disc. By contrast to normal SNR, CNR is measured in a narrow bandwidth centered at the carrier frequency.

In turn, full bandwidth SNR is related to the bit error rate (BER), which is ultimately a figure of merit for the quality of data storage and retrieval. The relationship between BER and SNR for a threshold detection system is given in Figure 6, which displays a pronounced increase in BER with decreasing SNR. The science behind this graph can be found elsewhere. [14]

![Figure 6. Dependence of bit error rate on signal to noise ratio over total bandwidth, taken from [14].](image)

To facilitate bit detection, equalization is typically employed in optical storage systems. [15] An improvement is achieved by electronically boosting the high-frequency response and, in this way, increasing the amplitude of intensity modulation generated by the smaller effects. On the media side, enhancing the optical contrast of the marking effects can increase the modulation amplitude. This aspect will be discussed in the upcoming chapters.
Figure 7. Focusing methods.
To realize accurate bit detection a number of functions of the drive have to be well under control. These include focusing and tracking. In order to stay in-focus and on-track a continuous adjustment of the lens-disc separation and of the radial position on the track are performed by the drive during read-out and recording. For this purpose the lens is mounted into an actuator, which allows electro-mechanically controlled movement of the lens. The focusing and tracking processes consist of a dynamic measurement of the amount and direction of de-focus and de-tracking and subsequently feeding this information into the actuator to do the appropriate corrections. Several methods exist to accomplish dynamic measurement of de-focus, see Figure 7. All these methods are based on making use of a special optical element that shapes the beam in a certain way depending on whether the laser beam is focused in front, behind or right onto the data layer of the disc. The element is complemented with a dedicated photo-detector. The element and the detector are placed into the laser beam reflected by the disc. In the case of the Foucault focusing method, a knife is positioned on the optical axis at the ideal focal point of the returning beam. Depending on the focus position the knife cuts a part of the beam, which is subsequently projected onto a split detector. By measuring the amount of light falling onto each part of the detector a focus error signal is derived. In the case of the astigmatic focusing method a cylindrical lens is placed in the returning beam. The lens creates perpendicularly oriented astigmatic lines on either side of the best focal point position. A quadrant detector is used to measure the relative intensity of these lines. In the spot-size focusing method the returning beam is split in two using a wedge. The two beams form two spots on the photo-detector. The size of the two spots mutually changes depending on the focus position. The focus error signal is derived from the relative size of the two spots. In all of the three cases the derived error signal has an S-shape. The intensity and polarity of the signal carry information on the amount and direction of defocus.
1. Introduction

Figure 8. Tracking methods.
There also exist several methods for dynamic measurements of the radial position on the track. The methods that are most commonly employed are explained in Figure 8. In the case of the radial push-pull tracking method use is made of the fact that the data track structure on the disc serves as a diffraction grating with a period of the track pitch. The interference between the diffraction order beams in the far-field carries information over landing of the incident laser beam on the data tracks. A four-quadrant detector is used to register the interference between the partly overlapping zeroth and first-order beams. The tracking error signal is derived from the difference signal and has a sine-shape, one period of which corresponds to one-track-pitch radial spacing on the disc. To realize 3-spot push-pull tracking a diffraction grating is placed in the light path of the drive to generate satellite beams. The whole setup is arranged such that when the main beam falls onto the center of a track the satellite beams land with a ½-trackpitch radial offset on either side of the track. The radial tracking error signal is generated by taking the (weighted) difference between the push-pull signal of the central spot and the push-pull signals of the two satellite spots. The 3-spot push-pull signal is more robust to beam landing offsets (displacement of the spot with respect to the detector due to e.g. misalignment) than the single spot push-pull signal and is, therefore, almost invariably used in practice. One more method that is often used for tracking is called differential phase (or time) detection, DPD or DTD. If a diffraction-limited spot lands onto a mark (pit) with a radial offset a timing difference between signals registered by the quadrants of a four-quadrant detector occurs. This difference is used to generate a tracking error signal. This error signal is particularly suitable for ROM-discs, where the marks needed to derive the signal are always present.

In the case of pre-recorded discs, the presence of marks (pits) and spaces (lands) is sufficient to generate the radial tracking error signal. In the case of recordable and rewritable discs where no data is originally present a groove structure is introduced into the disc to make tracking of an empty disc possible. During the data recording process the marking effects representing data are placed along the grooves.
1.2.3. Optical storage roadmap

The technology roadmap in optical storage is usually characterized by the disc capacity and data transfer rate. The overall trend is shown in Figure 9. The raise in storage capacity is achieved through increase in storage density (channel bit length and track pitch), number of data layers, and the efficiency of coding schemes and signal processing. Typical parameters, which characterize the trend are presented in Table 1. The density increase is realized by employing lasers with shorter wavelengths and objective lenses with a higher numerical aperture. Aided by coding efficiency, the storage densities that have been achieved in CD, DVD, and BD are 0.4 Gbit/inch$^2$, 2.8 Gbit/inch$^2$, and 14.7 Gbit/inch$^2$, respectively. The maximum velocity of the spinning disc limits data transfer rates. At 1x speed the transfer rates amount to 0.49 M bps (CD), 11 M bps (DVD), and 36 M bps (BD) with the maximum of 56x, 16x, and 12x for the three systems, respectively. This maximum data transfer rate is dictated by the servo characteristics of current optical drives rather than recording material or disc/substrate characteristics.

Figure 9. Optical disc storage technologies roadmap.
1.2.4. Optical media

An optical medium (often referred to as optical data carrier) typically comprises a disc-shaped substrate, one or more data layers, and a dummy substrate or a cover. Often, discs are complemented with labels carrying user information such as a table of contents of the data stored on the disc, etc. A cross-sectional view of a dual-layer DVD disc is given in Figure 10. The laser beam accesses the data layers through the bulk of a transparent material. One of the major advantages of such a media configuration is that the data layer is well protected from potential damage caused by disc handling. Typical defects such as scratches, fingerprints, dust etc. present on the disc surface are far out of focus of the addressing laser beam, and therefore hardly hamper the quality of the readout signals. In this way, the overall system robustness is greatly improved in comparison to direct contact systems, such as the vinyl LP-disc system and makes a cartridge kind of protection system redundant (like in hard disk drives or magnetic tape systems).

The technological choice of decreasing the laser wavelength and increasing NA of the objective lens in order to improve storage density comes at the cost of operating margins, such as disc tilt and focus error. In order to keep the margins at an acceptable level the thickness of the transparent material through which the data layer is accessed has to be reduced from 1.2 mm in the case of CD to 0.6 mm in the case of DVD to 0.1 mm in the case of BD. To facilitate backwards compatibility through the whole range of optical discs the total disc thickness needs to be kept at 1.2 mm. Thus, a CD is recorded and readout through the disc substrate whereas a BD is

Table 1. Characteristic parameters of CD, DVD, and BD systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CD</th>
<th>DVD</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength, nm</td>
<td>780</td>
<td>650</td>
<td>405</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.45/0.5</td>
<td>0.60/0.65</td>
<td>0.85</td>
</tr>
<tr>
<td>Track pitch, μm</td>
<td>1.6</td>
<td>0.74</td>
<td>0.32</td>
</tr>
<tr>
<td>Channel bit length, nm</td>
<td>277</td>
<td>133</td>
<td>74.5</td>
</tr>
<tr>
<td>Shortest effect length, nm</td>
<td>831</td>
<td>399</td>
<td>149</td>
</tr>
<tr>
<td>Modulation code</td>
<td>EFM</td>
<td>EFM+</td>
<td>17PP</td>
</tr>
<tr>
<td>Physical bit density, Gbit/inch²</td>
<td>0.4</td>
<td>2.8</td>
<td>14.7</td>
</tr>
<tr>
<td>Reference disc velocity 1x CLV, m/s</td>
<td>1.2</td>
<td>4.0</td>
<td>4.92</td>
</tr>
<tr>
<td>Substrate/cover thickness, mm</td>
<td>1.2</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Spot size, μm</td>
<td>0.9</td>
<td>0.55</td>
<td>0.238</td>
</tr>
<tr>
<td>Capacity per data layer, GB</td>
<td>0.65</td>
<td>4.7</td>
<td>25.0</td>
</tr>
<tr>
<td>Transfer rate at 1x speed, Mbit/s</td>
<td>4.3</td>
<td>11</td>
<td>36</td>
</tr>
</tbody>
</table>
accessed through a 0.1 mm thick cover, which is brought onto a 1.1 mm thick (dummy) substrate. A DVD comprises of two 0.6 mm thick substrates bonded back-to-back. The disc substrate is usually made of polycarbonate. This material is relatively easy to process via injection molding, it is transparent at the utilized laser wavelengths, and it is inexpensive and has a low moisture absorption resulting in a more stable shape. The cover layer is typically made of a polycarbonate sheet or a layer of resin.

Figure 10. A cross-sectional view of a dual-layer recordable DVD disc.

With respect to application, optical storage media can be divided into three types. The media types are usually being referred to as read-only (ROM), recordable or write-once (R or WO), and rewritable (RW or RE). The physical difference between these media is in the type and structure of the data layer.

The ROM media can only be read-out but cannot be erased or recorded. The data layer of such media contains pits replicated in the substrate during the disc manufacturing process. The manufacturing processes that are most widely employed are injection molding and photo-polymerization. The relief structure of the pits and lands is complemented with a thin reflective layer to facilitate readout of the data. Upon reflection from the pit and the land areas, rays of the laser beam gain a phase shift. Interference between the light rays results in modulation of the intensity of the reflected light. The depth and the width of the pits are chosen such that the intensity modulation is optimal.

In the case of R/WO/RW/RE media the marking effects representing the data are small recording marks formed in the recording data layer by the laser beam of the optical drive. The R/WO media can be written only once but read-out many times.
Many recording mechanisms and materials systems have been proposed to realize R/W/O media. These include hole burning, alloying of bi-layers, altering surface or interface roughness, agglomeration (island formation) in thin films, altering material state/phase, or bleaching. At present, most of the recordable CD and DVD discs are based on organic dyes. A layer of dye is typically brought onto the disc by a spin-coating process and is a part of a recording stack, which also comprises a metal and a dielectric layers. During recording the dye is locally heated and degraded (bleached) with a focused laser beam in an irreversible manner. The degradation is accompanied by a change in optical properties of the dye and the local geometry of the interface between the dye and the disc substrate. The intensity modulation during read-out is generated by both phase shift and amplitude change of the reflected laser light. The metal layer in the recording stack serves as a reflector and heat sink. The dielectric layer is used to enhance optical contrast between bleached and non-bleached areas of the dye, and for the purpose of chemical and mechanical protection in the stack. The BD-R standard allows also for inorganic material systems, like the Cu-Si system that is based on silicide formation upon laser heating.

1.2.5. Phase-change media

The RW/RE media can be written and readout many times. The technology utilized in rewritable media is based on laser-induced reversible amorphous-to-crystalline transitions in a thin phase-change film. The amorphous marks have typically a different reflection than their crystalline surrounding. The difference in reflection results in optical contrast that enables the readout of data. The readout principle is schematically illustrated in Figure 11. In the top panel a data pattern of amorphous marks in the crystalline matrix is shown, which is in this case visualized by Transmission Electron Microscopy (TEM). In the bottom panel a reflectivity profile corresponding to this data pattern is sketched. The amorphous marks result in a drop in the reflectivity level, which is detected as signal modulation.

Figure 11. Schematic of the readout principle of amorphous marks in a crystalline layer.
The phase-change layer is a part of the recording stack. It is sandwiched between so-called interference layers. A metallic layer is added to the stack on the side opposite to the entry side of the laser beam. A basic recording stack structure is sketched in Figure 12. For convenience, stacks are often denoted with a series of letters, MI\_1PI\_2 in the case considered here, where M stands for metal layer, I stands for interference layer, P stands for phase-change layer and so forth. The indices indicate the layer order in which the incident laser beam penetrates the stack.

Figure 12. Schematic of a phase-change recording stack.

All layers in the stack fulfill multiple functions. The phase-change layer acts as a signal modulation enabler and as a medium where data can be stored and erased. The metal layer works as a reflector and a heat sink. The interference layers serve for optical contrast enhancement, thermal resistance, and mechanical and chemical protection. Additional layers are often used to promote material crystallization, to improve the mechanical or chemical stability, etc. The thickness of the layers and their composition is of utmost importance for the recording stack performance.

Phase-change compositions that are used for rewritable optical discs are discussed in chapter 2. The high absorption coefficient and relative low thermal conductivity of these materials hamper mark formation (melting) in too thick phase-change layers. A too thin layer will not provide sufficient contrast between the amorphous and crystalline state, preventing the accurate detection of marks and decoding of data. Furthermore, a very thin phase-change layer may possess a low chemical stability.
The optimum thickness of the phase-change layer, typically between 5 and 30 nm, depends very much on the application. It is a compromise between good optical contrast, excellent recording properties and sufficient chemical stability.

A phase-change recording stack usually comprises a metallic layer for two important reasons. In the first place, the metals used possess a high absorption coefficient and a low index of refraction. In combination with the other layers in the recording stack, this leads to a high stack-reflection and an improved readout of the amorphous marks (improved modulation). In addition, the metals are used to improve the thermal response during writing and erasing of amorphous marks. Metals have a high thermal conductivity, which is favorable for the fast heat removal after melting of marks in the phase-change layer, the so-called melt-quenching process. Also for direct overwrite of the amorphous marks, when the old data need to be removed in a single passage during write of the new data, it is advantageous that the old marks are completely erased by heat diffusion ahead of the write pulse. Suitable metallic materials are alloys based on Ag, Al or Au and generally comprise a dopant to improve the chemical stability (for instance to control the grain size). For semi-transparent recording stacks, such as used in dual-layer phase-change discs, thin metallic layer or semitransparent heat sink layers, i.e. ITO, Al$_2$O$_3$ or HfN, can be applied to guarantee sufficient cooling rate and sufficient transmission to access the second recording stack as well. The application of these materials and their recording characteristics are discussed in chapter 5.

The dielectric film between the phase-change film and the metallic heat sink layer is primarily required to control the heat diffusion through the recording stack during erasing and writing of data. It acts as a thermal resistance for the heat flow into the metallic layer. In addition, the dielectric layers impose a stable chemical barrier to prevent diffusion of components out of the phase-change film. The dielectric layers contribute also to optimum optical stack characteristics. ZnS-SiO$_2$ is commonly used as dielectric interface material in a phase-change recording stack. It has a low thermal conductivity, it is optically transparent from 400 nm to 800 nm (thus for CD, DVD and BD applications), it has a relatively high index of refraction and it is thermally stable. A lot more materials have been considered for application in optical discs, such as HfN, Al$_2$O$_3$, and ITO but also SiC, Si$_3$N$_4$, TiO$_2$, SiO$_2$, etc. Of course, the applicability of these materials depends, among others, on the wavelength of the used laser light and the optical characteristics of the materials. The upper dielectric layer is primarily used to optimize the optical contrast of the recording stack. Also the high-temperature-resistant dielectric layer acts as a thermal barrier towards the substrate (CD, DVD) or cover layer (BD). ZnS-SiO$_2$ is also the preferred material.

1.3. Scope of this book

The main purpose of the book is to provide the reader with a detailed overview of the basics behind optical phase-change recording. Although the emphasis will be mainly on the material aspects of optical phase-change recording, in many cases it is inevitable to discuss hardware and signal processing details.
The layout of the book is as follows. Theoretical aspects of phase-change materials are dealt with in Chapter 2. In Chapter 3, the thermal modeling of phase-change recording is described and main characterization techniques and methodologies are explained. Chapter 4 gives an extensive analysis of the data storage process in rewritable phase-change media. Two main applications areas, namely high-speed and dual-layer recording are addressed in Chapter 5.

1.4. References Chapter 1


