Chapter 6

Optical Storage Media

In principle, optical storage media use the intensity of reflected laser light as an information source. A laser beam of approximately 780 nm wave length can be focused at approximately 1µm. In a polycarbonate substrate layer, we encounter holes, corresponding to the coded data, which are called pits. The areas between these pits are called lands. Figure 1 shows a cut through an optical disk along a track. In the middle of the figure, the lands and pits are schematically presented.

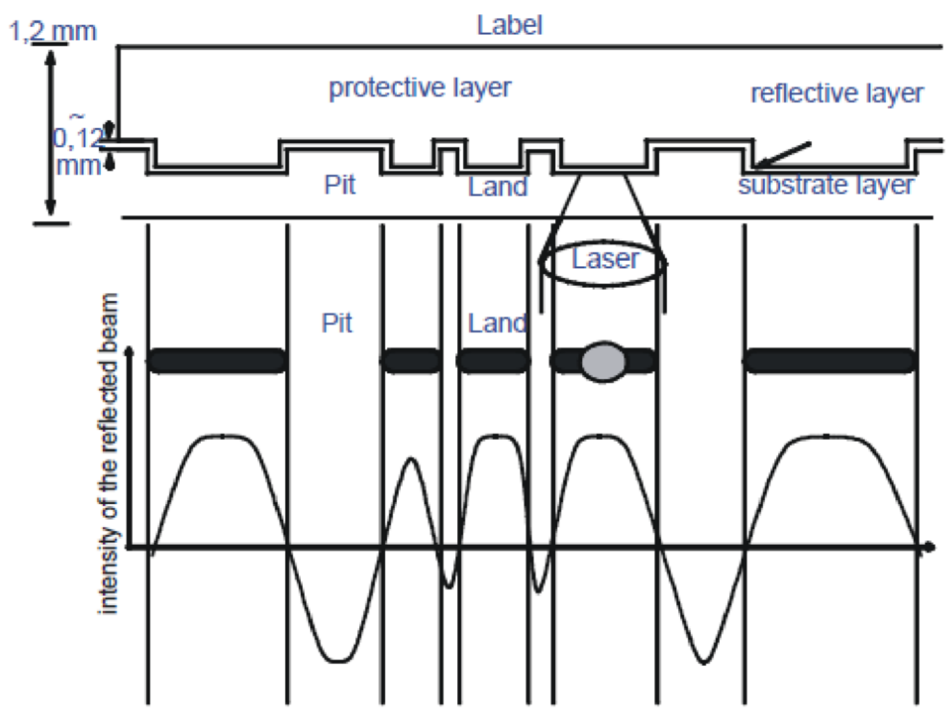

Figure 6.1: Cut through an optical disk along the data trace. A schematic presentation with the layers (above), the "lands" and the "pits" (in the middle), and the signal (below).

The substrate layer is covered with a thin reflective layer. The laser beam is focused on the reflective layer from the substrate layer. Therefore, the reflected beam has a strong intensity at the lands. The pits have a depth of 0.12 µm (from the substrate surface). The laser beam is lightly scattered at the pits, meaning it is reflected with a weak intensity. The signal, shown in figure, denotes schematically the intensity of the reflected beam-a horizontal line is drawn as the threshold value. Hence, according to figure, a compact disk consists of: The label

The protective layer

The reflective layer

The substrate layers

An optical disk consists of a sequential order of these pits and lands allocated in one track. Figure 2 shows an enlarged cut of such a structure.

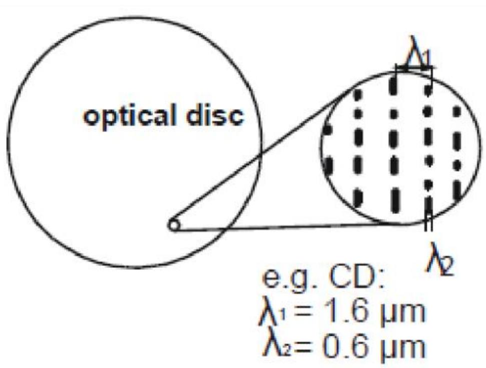

Figure 6.2: Data on a CD as an example of an optical disk (track with "lands" and "pits").

Information is stored in a spiral-shaped track:

- Series of **pits** and **lands** in substrate layer
- Transition from pit to land and from land to pit: ‘1’
- Between transitions: sequence of ‘0’ s
- 16000 turns/inch (tpi)

Reading: Laser focused onto reflective layer

- **Lands** - almost totally reflect the light
- **Pits** – scatter the light

The track is a spiral. In the case of a CD, the distance between the track is 1.6 µm. The track width of each pit is 0.6 µm. The pits themselves have different lengths. Using these measurements, the main advantage of the optical disk in comparison to magnetic disks is that on the former 1.66 data bits per µm can be stored. This results in a data density of

1,000,000 bits per mm^2, which implies 16,000 tracks per inch. In comparison, a floppy disk has 96 tracks per inch.

Advantages of Optical Storage Media

High data density

- 1.66 data bits/µm of track
- Inter-track density: 16000 tpi; compare diskette at 96 tpi

Long term storage

- Insensitive to magnetic/electric interference
- Insensitive to dust, scratches

Low probability of head crashes

- Distance between head and substrate surface > 1 mm

Adequate error correction

- allows handling of many defects

Perception quality

- e.g., each digital music disc is exactly equivalent to the master

Video Disks and Other WORMs

The video disk, in the form of Laser Vision, serves as the output of motion pictures and audio. The data are stored in an analog-coded format on the disk; the reproduced data meet the highest quality requirements. The Laser Vision disk has a diameter of approximately 30 cm and stores approximately 2.6 Gigabytes.

Video disk was designed as Read Only Memory (ROM), many different write-once optical storage systems have come out, known as the Write Once Read Many (WORM) disks. An example is the Interactive Video Disk. This disk is played at a Constant Angular Velocity (CAV). On each side, 36 minutes of audio and video at a rate of 30 frames per second can be stored and retrieved. One can also store around 54,000 studio quality images per side.

A write once read many or WORM drive is a data storage device where information, once written, cannot be modified. On ordinary data storage devices, the number of times data can be modified is not limited, except by the rated lifespan of the device, as modification involves physical changes that may cause wear to the device. The "read many" aspect is unremarkable, as modern storage devices permit unlimited reading of data once written.

WORM devices are useful in archiving information when users want the security of knowing it has not been modified since the initial write, which might imply tampering. The CD-R and DVD-R optical disks for computers are common WORM devices.

Write-once storage media have a capacity between 600 Mega Bytes (MB) and approximately 8 Gigabytes. The diameter of the disks is between 3.5 and 14 inches. The main advantage of a WORM disk, compared to other mass storage media, is the ability to store large amounts of data which may not be changed later, i.e., an archive which is secure. To increase capacity, juke-boxes are available, which allow the stocking of several disks and lead to capacities of over 20 Gigabytes.

Compact Disk Digital Audio

The first CD format was of course that which defined the audio CD used in all regular CD players, called *CD Digital Audio* or *CD-DA* for short. The specifications for this format were codified in the first CD standard, the so-called "red book" that was developed by Philips and Sony, the creators of the original compact disk technology. The "red book" was published in 1980, and actually specifies not just the data format for digital audio but also the physical specifications for compact disks: the size of the media, the spacing of the tracks, etc. In a sense, then, all of the subsequent standards that came after CD-DA build on the "red book" specification, since they use the same specifications for the media and how it is read. They also base their structure on the original structure created for CD audio.

Data in the CD digital audio format is encoded by starting with a source sound file, and sampling it to convert it to digital format. CD-DA audio uses a sample rate of 44.1 kHz, which is roughly double the highest frequency audible by humans (around 22 kHz.) Each sample is 16 bits in size, and the sampling is done in stereo. Therefore, each second of sound takes (44,100 * 2 * 2) bytes of data, which is 176,400 bytes.

Audio data is stored on the disk in blocks, which are also sometimes called sectors. Each block holds 2,352 bytes of data, with an additional number of bytes used for error detection and correction, as well as control structures. Therefore, 75 blocks are required for each second of sound. On a standard 74-minute CD then, the total amount of storage is (2,352 * 75 * 74 * 60), which is 783,216,000 bytes or about 747 MB. From this derives the handy rule of thumb that a minute of CD audio takes about 10 MB, uncompressed.

CD-DA: Characteristics Audio data rate

The audio data rate can be easily derived from the given samples frequency of 44.1 kHz and the 16-bit linear quantization. The stereo-audio signal obeys the pulse-code modulation rules and the following audio data rate is derived:

- Sampling frequency: 44,100 Hz
- Quantization: 16 bits
- Pulse code modulation (PCM), uniform quantization
- Audio data rate = 1,411,200 bit/s = (~ 1.4 Mbit/s) (stereo)

$$Audiodatar \quad ate_{CD-DA} = 16 \frac{bits}{samples} \times 2 channels \times 44100 \frac{samples}{s \times channel}$$

$$= 1,411,200 \frac{bits}{s} = 1,411,200 \frac{bits / s}{8 bitst / byte}$$

$$= 176.4 \frac{kbytes}{s} \cong 172.3 \frac{Kbytes}{s}$$

Quality

Analog LPs and cassette tapes have a signal-to-noise ratio between 50 dB and 60 dB. The quality of the CD-DA is substantially higher. As a first approximation, we can assume 6 dB per bit during the sampling process. Hence, with 16-bit linear sampling, we obtain the following:

- Signal to noise ratio (S/N): ~ 6 dB/bit, 16 bit quantization => S/N exactly 98 dB
- Compare LP, tape: S/N 50-60 dB

$$S/N_{CD\text{-}DA} \cong 6\frac{dB}{bit} \times 16\,bits = 96\,dB\,(decibel)$$

The signal-to-noise ratio is exactly 98 dB.

Capacity (without error correction data)

A CD-DA play time is at least 74 minutes. With this value, the capacity of a CD-DA can be easily determined. The following example shows the computation of a capacity for pure audio data without taking into consideration additional information such as error correction:

- Playback time: maximal 74 min
- Raw capacity =74 min x 1,411,200 bit/s = 6265728000 bit ~ 747 Mbyte

$$Capacity_{CD\text{-}DA} = 74 \text{ min} \times 1{,}411{,}200\,\frac{bits}{s} = 6{,}265{,}728{,}000\,bits$$

$$= 6{,}265{,}728{,}000\,bits \times \frac{1}{8\frac{bits}{byte}} \times \frac{1}{1024\frac{bytes}{Kbyte}} \times \frac{1}{\frac{Kbytes}{Mbyte}} \cong 747\,Mbytes$$

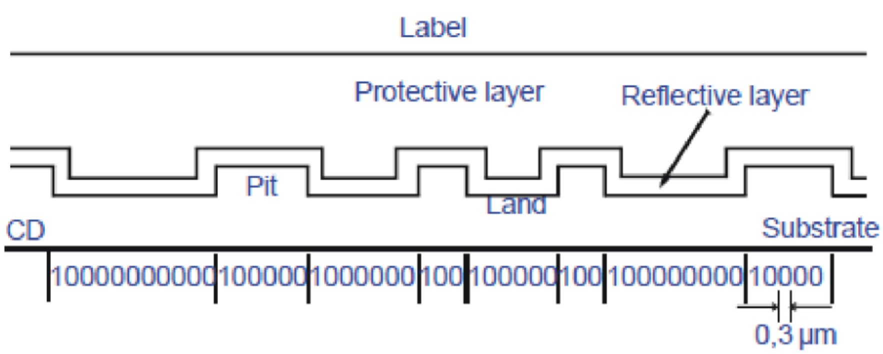

Figure 6.3: Lands and pits with their related digital data stream.

Length of pits and lands: multiples of 0.3 µm.

CD-DA: Eight-to-Fourteen Modulation

Restricted laser resolution

Requires a minimal distance between transitions (pit to land, land to pit): at least two “0”s between two “1”s

Generation (adaptation) of the clock signal is driven by transitions

Requires a maximal distance between transitions (pit to land, land to pit): not more than 10 consecutive “0”

For these reasons, the bits written on a CD-DA, in the form of pits and lands, do not directly correspond to the actual information; before recording, Eight-to-Fourteen Modulation is applied. Using this transformation, the regularity of the minimal and maximal distances is met.

- An 8-bit data value is encoded using 14 bits
- 267 combinations fulfill the criteria above, 256 are chosen. Criterion: efficient implementation with a small number of gates.

Example for the code conversion table

Audio Bits	Modulation Bits
00000000	01001000100000
00000001	10000100000000

But: a concatenation of two independent 14-bit values could lead to a violation of:

- minimum distance of 2 bits between Ones
- maximum distance of 10 bits between Ones

Therefore, three additional ***merging (filling) bits*** are inserted between two consecutive modulation symbols so that the required regularity can be met. The filling bits are chosen depending on the neighboring bits.

CD-DA: Eight-to-Fourteen Modulation Example

Audio Bits	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
Modulation Bits	0 1 0 0 1 0 0 0 1 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0
Filling Bits	0 1 0 1 0 0
Channel Bits	0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 0 0 1 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0
On the CD-DA	l p p p l l l p p p p l l l l l l p p p l l l l l p p p p p p p p p

CD-DA: Error Handling

The goal of error handling on a CD-DA is the detection and correction of typical error patterns. A typical error, a consequence of a scratch and /or pollution, can be characterized as a burst error.

A two-stage error correction is implemented according to the *Reed Solomon algorithm*:

First level: byte level, EDC and ECC. Two groups, each with four correction bytes for 24 data bytes:

- 1st group: correction of single byte errors
- 2nd group: correction of double byte errors, detection of additional errors **Second level: frame interleaving**
- frame: 588 channel bits for 24 audio data bytes
- distribution of consecutive data bytes and corresponding ECC bytes over adjacent frames

Compact Disk Read Only Memory

The Compact Disk Read Only Memory (CD-ROM) was designed as the storage format for general computer data - in addition to uncompressed audio data.

CD-DA provides a suitable means for the handling of typical errors caused by damage or dust. The CD-DA specification became the basis of a **family** of optical storage media.

But not conceived for:

- video (different ECC, EDC scheme required)
- discrete data (error rate too high)

- simultaneous play back of various media

For computers there is a need for storage of:

- Data, audio, compressed audio and video

The Yellow Book CD-ROM Standard

- CD-ROM mode 1: for any data
- CD-ROM mode 2: for compressed audio and video data
- But cannot be combined on a single track

Within a single track:

- Only CD-DA audio or only CD-ROM specific data

Mixed Mode Disc:

- Data tracks at the beginning
- Subsequent tracks for audio data

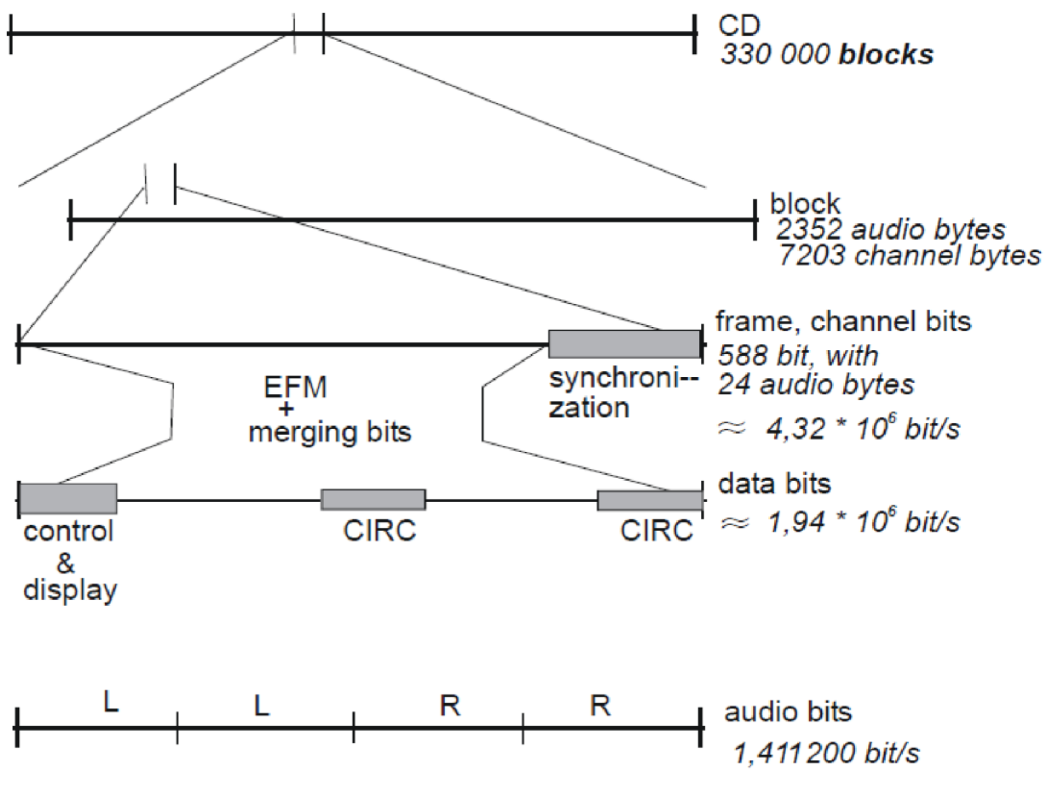

Figure 6.4: CD-ROM data hierarchy with audio data.

CD-ROM: Structure

Fine granularity for random access

- Tracks and Index Points not sufficient
- Structure with a higher resolution: the **block**
- Blocks contain a fixed number of frames

Disk structure

- 1 block = 32 frames
- 75 blocks/s (for a single-speed CD-ROM)
- 1411200 bit/s / 75 blocks/s / 8 bits/byte = 2352 bytes/block

Allows for

- Random access
- Better EDC, ECC

CD-ROM Mode

The CD-ROM was specified with the following goal: it should serve to hold uncompressed CD-DA data and computer data. This goal is achieved by introducing two modes: mode 1 and mode 2.

CD-ROM Mode 1

The block contains 2,048 bytes for information storage out of the available 2,352 bytes.

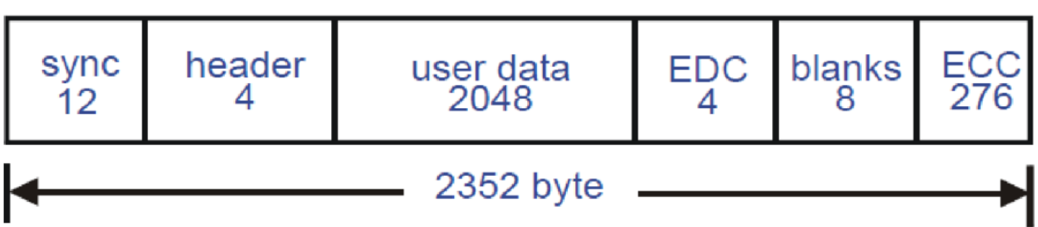

Figure 6.5: CD-ROM mode 1 block layout

The 2,352 bytes are split into the following groups:

- *12 bytes for synchronization; i.e.,* for the detection of the block beginning.
- *4 bytes for the header,* which carries an unambiguous specification of the block. The first byte stores minutes, the second byte stores seconds and the third byte contain the block number. The fourth byte includes the mode specification.
- *2,048 bytes* for the user data.
- *4 bytes* for error detection.
- *8 unused bytes.*
- *276 bytes* for error correction.

A CD-ROM contains 333,000 blocks to be played in 74 minutes. The capacity of a CD-ROM with all blocks in mode 1 can be computed as follows:

$$Capacity_{CD-ROM\ \bmod e1} = 333{,}000\ blocks \times 2048\ \frac{bytes}{block} = 681{,}984{,}000\ bytes$$

$$= 681{,}984{,}000 \times \frac{1}{1024\ \frac{bytes}{Kbytes}} \times \frac{1}{1024\ \frac{Kbytes}{Mbyte}} \approx 660\ Mbytes$$

The data rate in mode 1 is:

$$Rate_{CD-ROM\ \bmod e1} = 2{,}048\ \frac{bytes}{Blocks} \times 75\ \frac{Blocks}{s} = 153.6\ \frac{Kbytes}{s} \equiv 150\ \frac{Kbytes}{s}$$

CD-ROM Mode 2

CD-ROM mode 2 holds data of any media. The data layout of a CD-ROM block in mode 2 is shown in Figure 6.

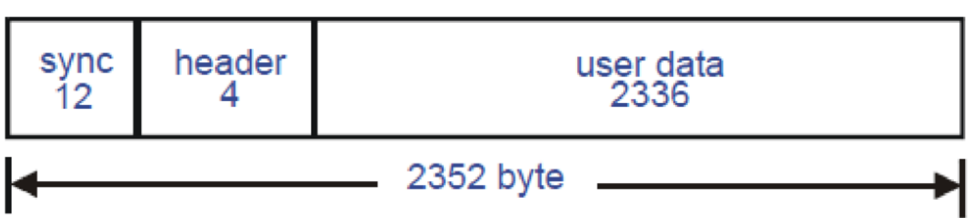

Figure 6.6: CD-ROM mode 2 block layout

The capacity and data rate of a CD-ROM with all blocks in mode 2 be computed as follows:

$$Capacity_{CD-ROM\ \bmod e2} = 333{,}000\ blocks \times 2336\ \frac{bytes}{block} \approx 777{,}888{,}000\ bytes$$

$$Rate_{CD-ROM\ \bmod e2} = 2336\ \frac{bytes}{Blocks} \times 75\,blocks\ /\ s \approx 175.2\,Kbyets\ /\ s$$

CD-ROM Extended Architecture

The Compact Disk Read Only Memory/Extended Architecture (CD-ROM/XA) standard was established by N.V. Phillips and the Sony and Microsoft Corporations and is based on the CD-ROM specification.

CD-ROM/XA differentiates blocks with form 1 and form 2 formats. This is similar to the CD-ROM modes:

CD-ROM/XA Form 1

This CD-ROM mode 2 XA format provides improved error detection and correction. Analogous to the CD-ROM mode 1, four bytes are needed for detection and 276 bytes for correction. Contrary to CD-ROM mode 1, the unused eight bytes of mode 1 are used for sub headers. Figure 7 shows a block where 2,048 bytes are used as data.

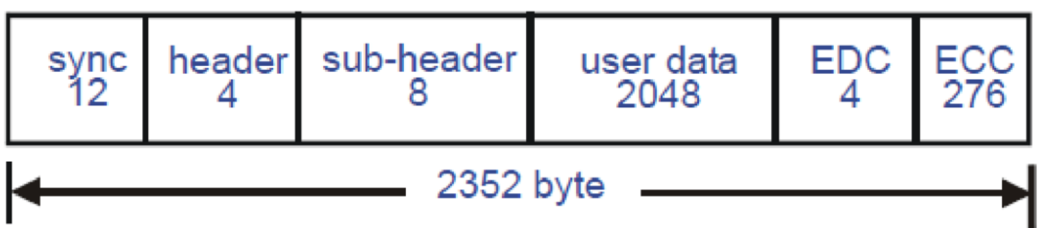

Figure 6.7: CD-ROM/XA block layout according to "Green Book" - layout of a CD-ROM block in mode 2, form 1

CD-ROM/XA Form 2

This CD-ROM mode 2 XA format allows 13% more storage capacity out of the entire block size (2,352 bytes) for user data, which means 2,324 bytes for user data. This is gained at the expense of worse error handling. In these form 2 blocks, compressed data of different media, including audio and video, can be stored.

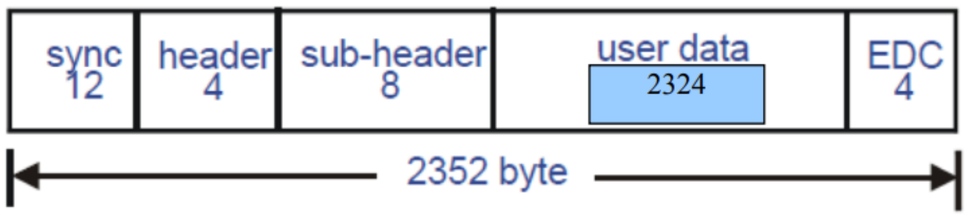

Figure 6.8: CD-ROM/XA block layout according to the "Green Book" - layout of a CD-ROM block in mode 2, form 2.

Principle of the CD-WO

The Compact Disk Write Once (CD-WO), like WORM (Write Once Read Many), allows the user to write once to a CD and afterwards to read it many times.

In the case of a CD-WO, an absorption layer exists between the substrate and the reflective layer. This layer can be irreversible change of the reflection characteristics by heating up the absorption layer ("burning"). The absorption layer in the pre-grooved track is heated to above 250^0C with a laser three to four times the intensity of a reading player.

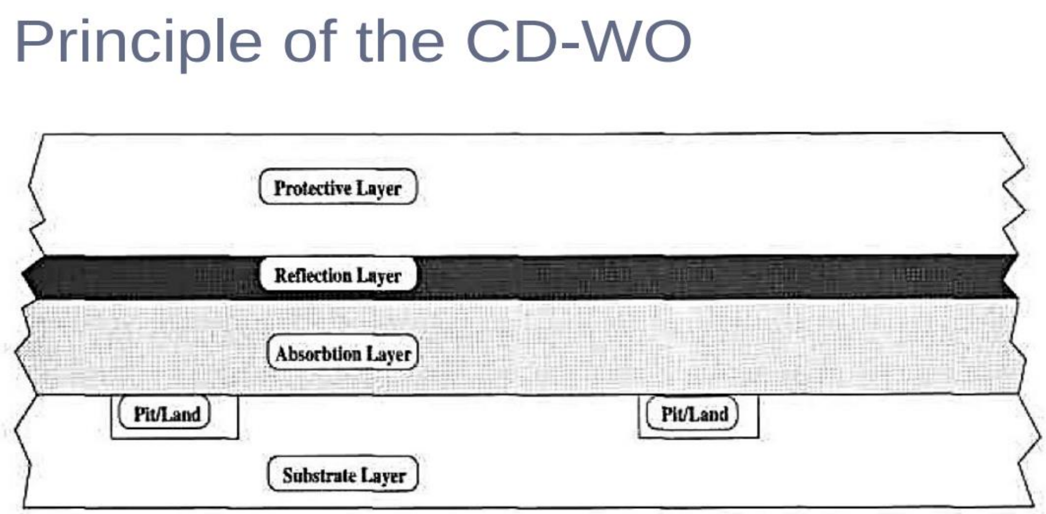

Figure 7.12: *Cross-section of a CD-WO disk.*

CD-MO: Compact Disc Magneto Optical

The Compact Disk Magneto Optical (CD-MO) has a high storage capacity and allows on to write multiple times to the CD.

The magnetic-optical method is based on the polarization of the magnetic field where the polarization is caused by a heat.

To be written, the block (sector) is heated to above 150^0C. Simultaneously, a magnetic field approximately 10 times the strength of the earth's magnetic field is created. The individual dipoles in the material are then polarized according to this magnetic field. Hereby, a pit corresponds to a low value of the magnetic field. A land is coded through a high value of the magnetic field.

After the CD is irradiated with a laser beam, the polarization of the light changes corresponding to the existing magnetization. Using this process, the read operation is executed.

For a delete activity a constant magnetic field is created in the area of a block and the sector is simultaneously heated.

Feature:

- Write data
- Read data
- Erase data
- Rewrite data

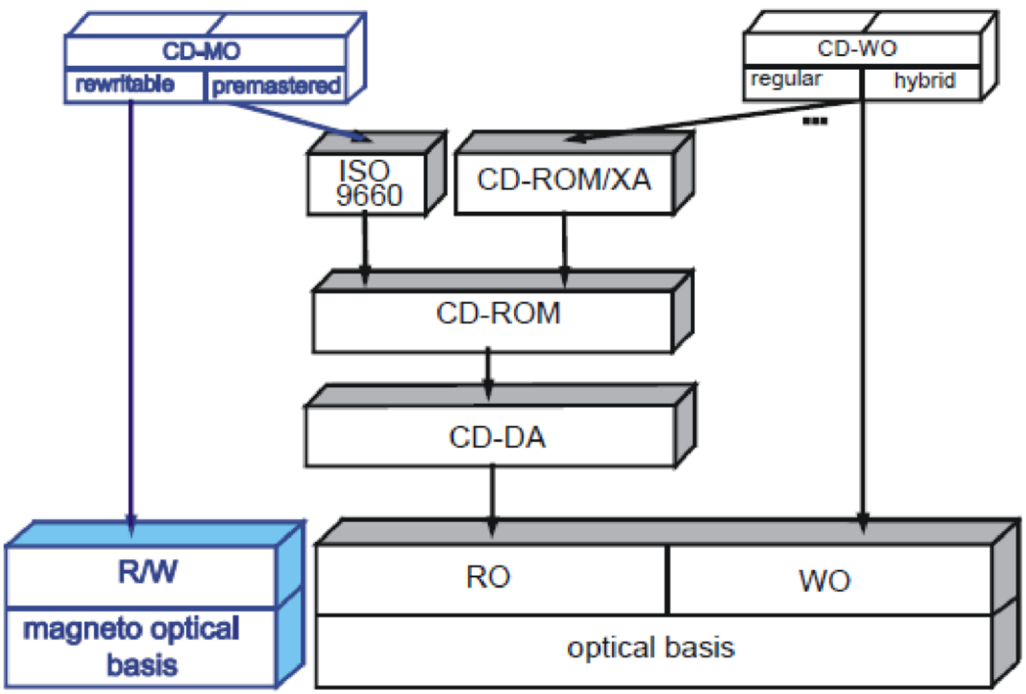

Figure 6.9: CD-WO and CD-M