Optical Recording and Recordable DVD Overview

Koichi Sadashige
Sadashige Associates
15 Amherst Rd, Voorhees NJ 08043-4901
Phone: +1-856-767-2644, FAX: +1-856-767-1462
e-mail: mm306@msn.com

Optical Recording

The expression *optical recording* is often used loosely by both engineers and marketing executives. Nearly all recording systems, where a focused laser beam is used in either writing or reading, are normally referred to as optical recording.

There are four basic types of optical recording, shown in Fig 1. All four are currently in use and although they are all applicable to both disc and tape, only disc products are available at the moment.

1. Change of physical dimension: Data recording changes the dimension, generally the thickness, of the media. The 1's are thicker than the 0's, or *vice versa*. Removing the material, or replicating a master recording by injection molding, which produces a medium with thickness variations representing the recorded data, can make the recording. CD-Audio, CD-ROM, DVD-Video and DVD-ROM media are volume produced through the injection molding process. The material removal recording, used since at least the beginning of recorded history, may become fashionable again in the future, using nanoscale technology.

2. Magnetic Recording: By raising the temperature of the medium to close to its Curie point, a weak magnetic field can be used to reverse the existing polarity of the bit cell on a track. The recorded pit size and shape are defined by the diameter and the on-time duration of the laser beam used as the heat source. This is the basic form of Magneto-Optical (MO) recording.

3. State Transition: Certain alloys of elements from the group VI of the periodic table can be caused to transition between amorphous and crystalline states by controlled heating and cooling. These alloys are stable in both states at room temperature. This technique is often referred to as Phase Change (PC) recording. On the medium, which is in the polycrystalline state, recording is accomplished by rapidly heating the material with a laser and letting it cool quickly to the amorphous state. As with MO recording, the PC process is completely reversible. PC recording is the basis for DVD-RAM, and the proposed newer format, "DVD-Video Recording".

4. Polymer Dye Burn-In: In this irreversible process, data is burned onto the medium whose surface contains a polymer dye. CD-R, and DVD-R belong to this recording category.

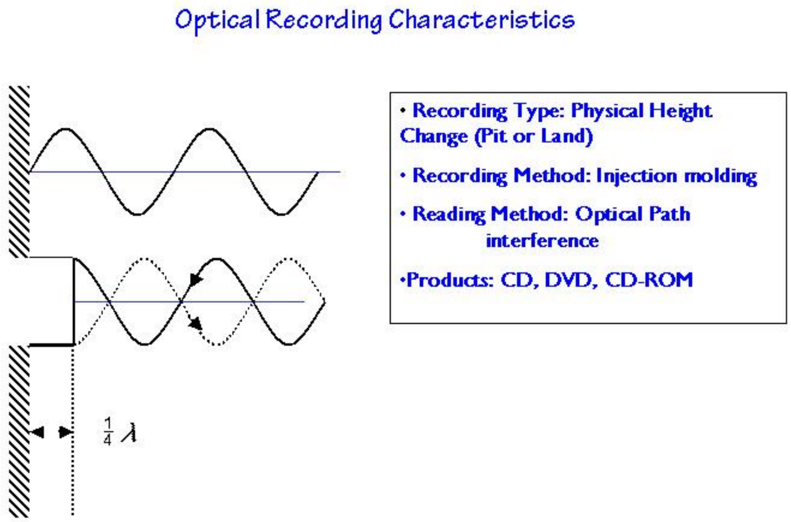


Figure 1a. Optical Recording Characteristics: Land and Pit recording

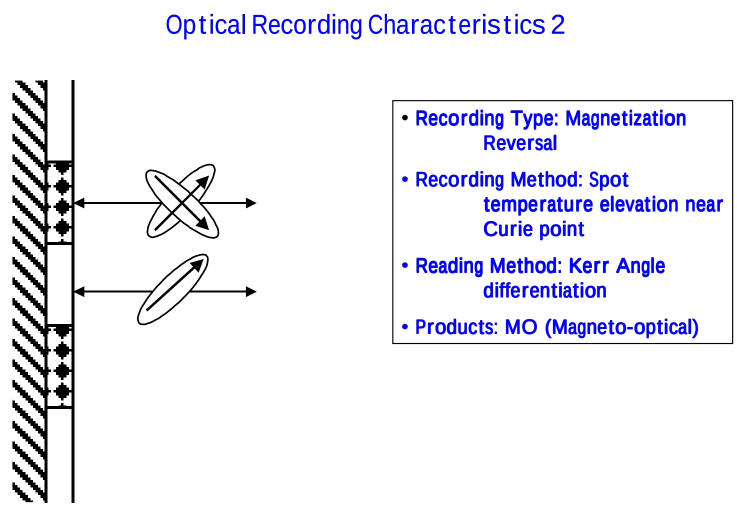


Figure 1b. Optical Recording Characteristics: Magneto-optical recording

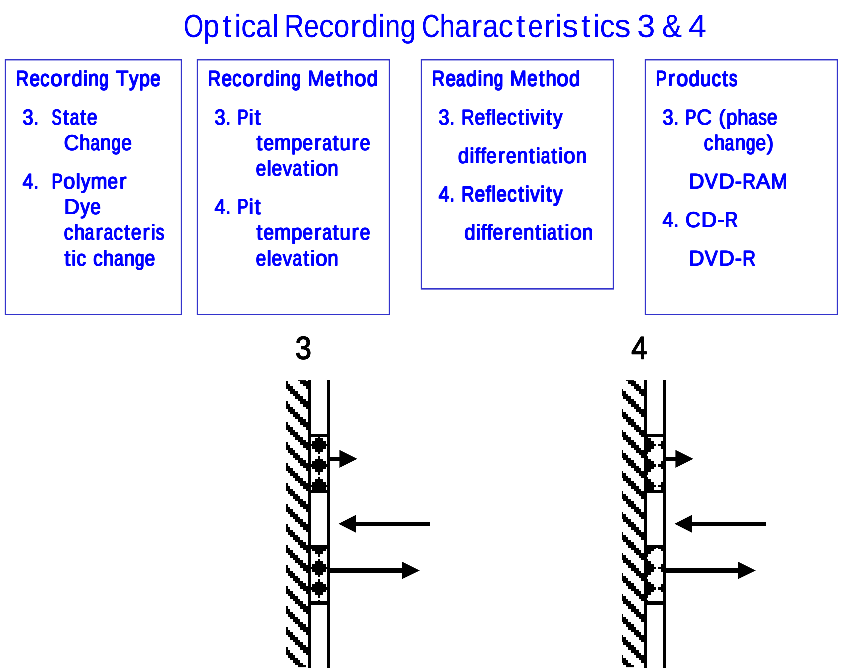


Figure 1c. Optical Recording Characteristics: Polymer Dye and Phase Change

Data Recovery

In technologies 1, 3 and 4, the reflectivity difference between recorded and unrecorded areas is detected and used to generate an electronic signal.

In CD-Audio, CD-ROM, DVD-video and DVD-ROM, which are replicated by injection molding, the effective elevation difference between recorded (pit) and unrecorded (land) areas is $\lambda/4$, leading to near cancellation of light reflected from the recording area; here λ is the laser wavelength.

In PC media, the polycrystalline state has a higher reflectivity than the amorphous state.

On polymer dye media, the burned-in spots have lower reflectivity than the unrecorded areas.

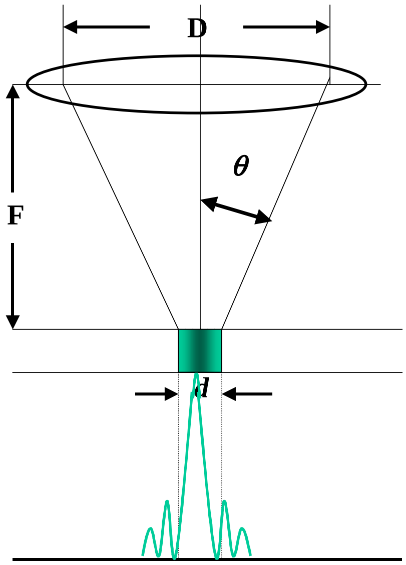
When reflected off a magnetized surface, the plane of polarization of a polarized beam is rotated with respect to the incoming beam, a phenomenon known as the *Kerr effect*, discovered in 1877 by John Kerr. In MO recording, this small rotation is used to generate the read signal.

Factors determining Optical Recording Density

The diameter of the focused laser beam is the determinant of areal density except in the case of injection-molded media. The diffraction-limited spot diameter is given by the expression

$$d = C\lambda/NA$$

Where NA is the numerical aperture of the lens and the proportionality constant depends on the factors illustrated in Fig 2.



f number = F/D

Numerical aperture, NA = *sin* θ

$$NA = \frac{D/2}{(F^2 + D^2/4)^{1/2}}$$

Spot size = *d*

$d = \sigma\lambda/NA$

Where λ = wavelength of laser

σ = factor determined by beam energy distribution

Figure 2. Factors determining spot diameter and their relationship

The numerical aperture is the sine of the solid angle as viewed from the focal point of the lens to the lens's maximum radius. The larger the NA, the faster the lens, as opposed to the commonly used lens speed expression of *f*-number. A smaller *f*-number indicates a faster lens. Theoretically NA cannot exceed unity, and the *f*-number cannot be smaller than 0.5.

For an optical recording drive to be practical -- physically small, reasonably priced, and requiring no external support equipment -- the laser must be a semiconductor type. Since the early 1980's, diode lasers operating in the near infrared wavelength, 900 to 800 μm -- have been available.

A single group lens with NA of 0.4 to 0.5 (corresponding to *f*-numbers of 1.2 to 0.9) can be manufactured inexpensively.

Based on these numbers, *i.e.*, the wavelength of 800 ~ 900 μm and NA of 0.4 to 0.5, the spot size comes out to be 1 to 0.8 μm.

The track pitch in optical recording is twice the spot diameter, and this almost completely eliminates inter-track interference. Further, by choosing the spot diameter as the minimum mark length, a density of 1.5 to 2 μm^2 can be achieved. This was believed to be achievable in the early 80's during the period leading up to the development of what came to be known as Compact Disc Technology.

Comparison with Magnetic Recording

If one studies the evolution of hard disk drives in the 70's and 80's, an interesting fact emerges. Fig. 3 shows the areal density of representative hard disc drives during this period. In the early 1980's, when optical recording was just moving from an engineering concept to the state of marketable product development, the HDD was operating at a density of 10 to 20 Mb/in^2, or 30 to 60 μm^2/bit. At that time, these figures were a factor of 20 to 30 smaller than what could be realized optically with available components.

	1970	1980	1984	1985	1990	1999	2000+
Product	3330	3380	3480	ID-1	Corsair	Micro-drive	1999 Demo
TPI	192	801	36	655	2,238	19,000	67,300
Kbits/in	4.04	15.2	49.4	50.8	58.9	265	522
Mb/in^2	0.776	12.2	1.78	33.3	89.5	5,035	35,300
μm^2/bit	830	53	362	19.4	7.2	0.128	0.0018

Figure 3. Growth of Magnetic Recording Areal Density

This explains why optical recording was, and still is, considered synonymous with high-density recording.

Tape recording was not much better than the disc recording. The first generation digital video recording format, D-1, entering the marketplace in 1981, had a 20 μm^2/bit. For purposes of comparison, the Fig 3 also shows the recording density of IBM-3480, the first cartridge tape data recording system, 362 μm^2/bit.

Details of the CD-Audio disc, as it finally entered volume production in early 1980's, are shown in Fig.4 CD-ROM has essentially the same characteristics, and it is produced by the same process, *viz.*, injection molding. All CD derivatives operate at the same recording density.

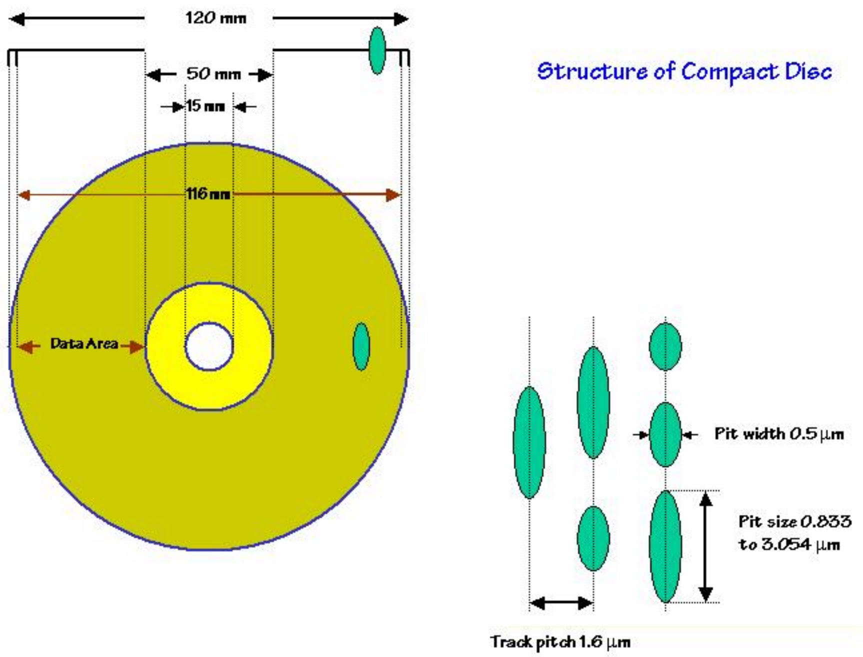


Figure 4. Structure of Compact Disc

The Road to DVD

The CD and its derivative products were the first volume-produced digital recording systems with an inexpensive storage medium. Its data holding capacity of 680 MB was a remarkable achievement when compared to the then standard data storage medium of IBM-3480 cartridge, with a capacity of 200 MB. The volume of the 3480 cartridge, 300 cm^3, is more than twice that of a CD in its protective plastic case.

New applications for both non-recordable mass replicated formats as well as recordable formats based on the CD technology emerged in 1980's and early 1990's.

The most notable one was the Video CD, which stores MPEG-1 compressed video of one-hour duration.

Unlike magnetic recording, where incremental performance improvements are practical and thus being introduced by manufacturers on frequent intervals, the CD has maintained its fundamental physical and optical characteristics intact for a considerable period of time.

During the intervening years, however, components, technology, and signal processing techniques, all directly applicable to optical recording, have made significant progress.

For the next generation Optical Disc Recording format, two technical consortia proposed remarkably similar systems. The two systems, however, contained minor, yet completely incompatible, technical details.

After fierce competition and much argument, the two groups agreed to join forces and develop a unified, single technical approach for the highly versatile, video, audio, and data compatible optical disc format of very high data holding capacity.

DVD, the digital versatile disc product line was born in December 1995.

DVD is a family of products, and specifications for new product configurations are constantly being developed and also being updated.

The first volume-produced product, the "DVD-Video", has approximately seven times the data capacity of the CD, or 4.7 GB per surface.

This capacity, 4.7 GB, has since become the yardstick against which the capability of all subsequent DVD products are measured. Recordable DVD formats, DVD-R, DVR-RW, and DVD-RAM, which did not meet this target initially, are now working toward the 4.7 GB per surface capacity objective.

DVD-Video incorporated following technical innovations to achieve the seven-fold capacity increase possible. Details of DVD-Video disc is shown in Fig. 5.

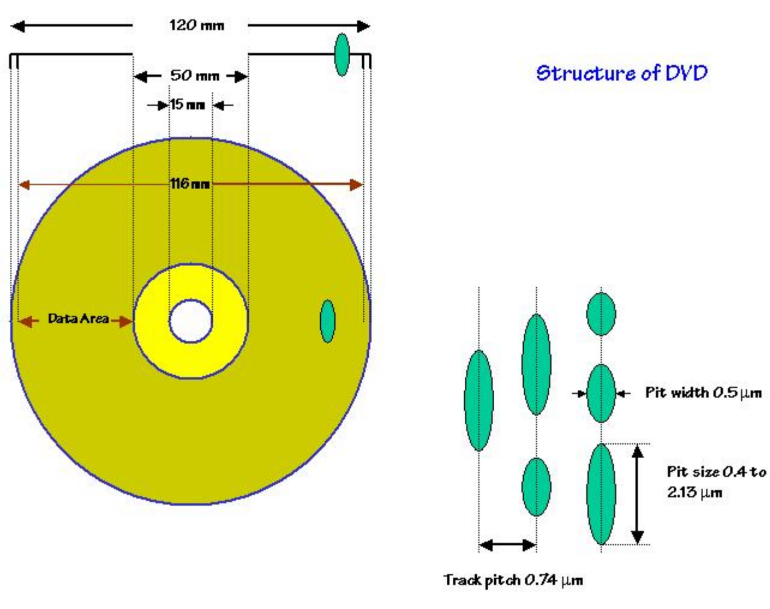


Figure 5. DVD-Video Disc

1. Laser wavelength shortened from 780 nm to 650/635 nm
2. Objective lens numerical aperture widened from 0.45 to 0.60

The effects of these two improvements were the reduction of track pitch from 1.6 to 0.74 μm, and shortening of the minimum mark length from 0.833 to 0.40 μm, or an areal density increase of 4.5.

3. The channel code was changed from 8 – 14 modulation (EFM) to 8 – 16 modulation, making a modest but important gain in the linear track density of 7%. (Even though the CD modulation code is EFM, three *merge* bits were used with each channel symbol, effectively making it an 8-17 code)

4. The Error Correction Code was improved. While it had become more powerful in correcting longer burst errors, its overhead was reduced from 30% to 15%.

In addition, DVD has incorporated a double layer data storage technology. Both recorded layers face the front side of the disc, making it possible to read the data from the same side, without flipping the disc. Since the signal from the bottom layer must be read through the front layer, the front recording reflective layer is semi-transparent.
Because of these added limitations imposed on the data-holding layers, the two-layer, front-readable DVD-Video has a combined capacity of 8.5 GB.

Phase Change Recording

Like the CD family of products, DVD also has a number of recordable formats. The first recordable DVD, DVD-R, is a higher density version of CD-R, whose basic characteristics have been discussed earlier.

Perhaps the most important DVD product for the data storage application is the DVD-RAM, which operates like a magnetic tape recorder, with some additional desirable features.

DVD-RAM is based on the Phase Change (PC) recording principle.

Alloys composed of such metals as Tellurium, Selenium, Antimony, Tin, Germanium and Silver have characteristics of transitioning between amorphous and polycrystalline states when subjected to temperature cycles.

Some alloys are more stable than others in each state. Rapidly heating the alloy to its melting point, and quickly cooling it can change it from the polycrystalline state to the amorphous state.

To revert to the polycrystalline state, the amorphous state alloy is heated to a temperature just above its crystallization point, then allowed to cool naturally to crystallize itself. The phase change processes are shown in Fig.6. The alloy has a higher level of light reflectivity when it is in crystalline state than when it is in amorphous state. This is the basic operation of phase change recording. The change in the light reflectivity is detected as the recorded data output.

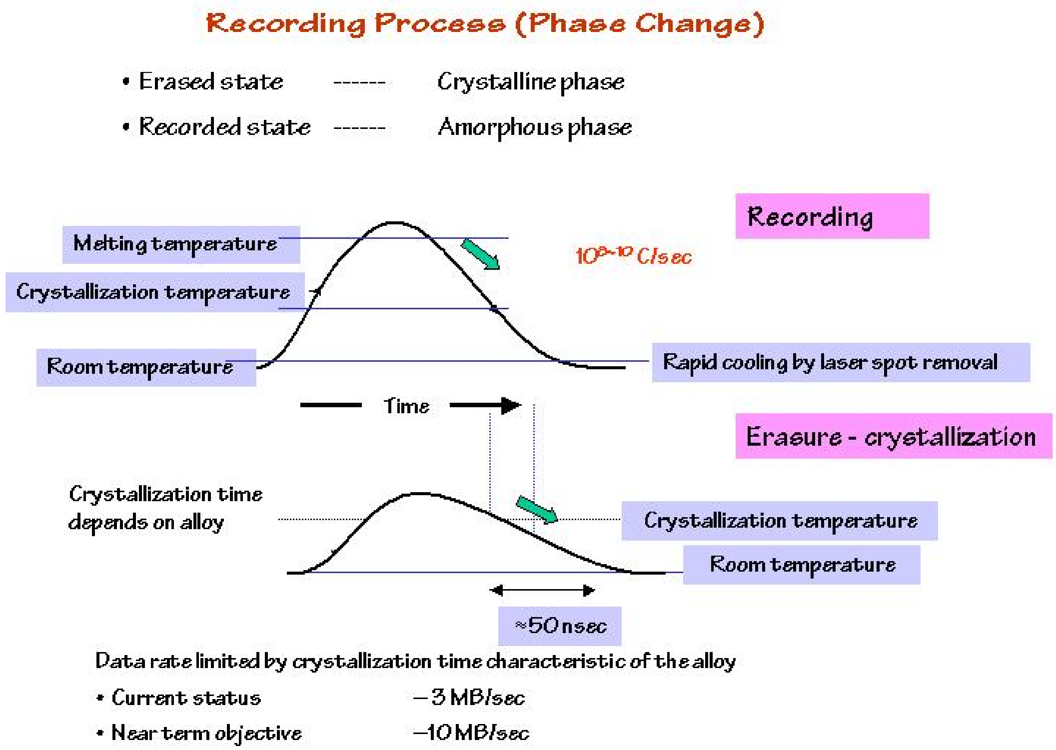


Figure 6. Recording Process in Phase Change (PC) Media

An alloy of Te and Sb is preferred both for its environmental stability and large reflectivity change between states (typically <5% reflectivity in the amorphous state, and >20% in the crystalline state). Some other materials, such as Germanium, Indium, and Silver are often added to the basic alloy to improve its optical characteristics.

The structure of a typical phase change recording disc is shown in Fig.7. Thickness of the recording layer is ~20 nanometer, and its thickness significantly influences its lateral heat conductivity, which, in turn, controls the achievable data recording rate.

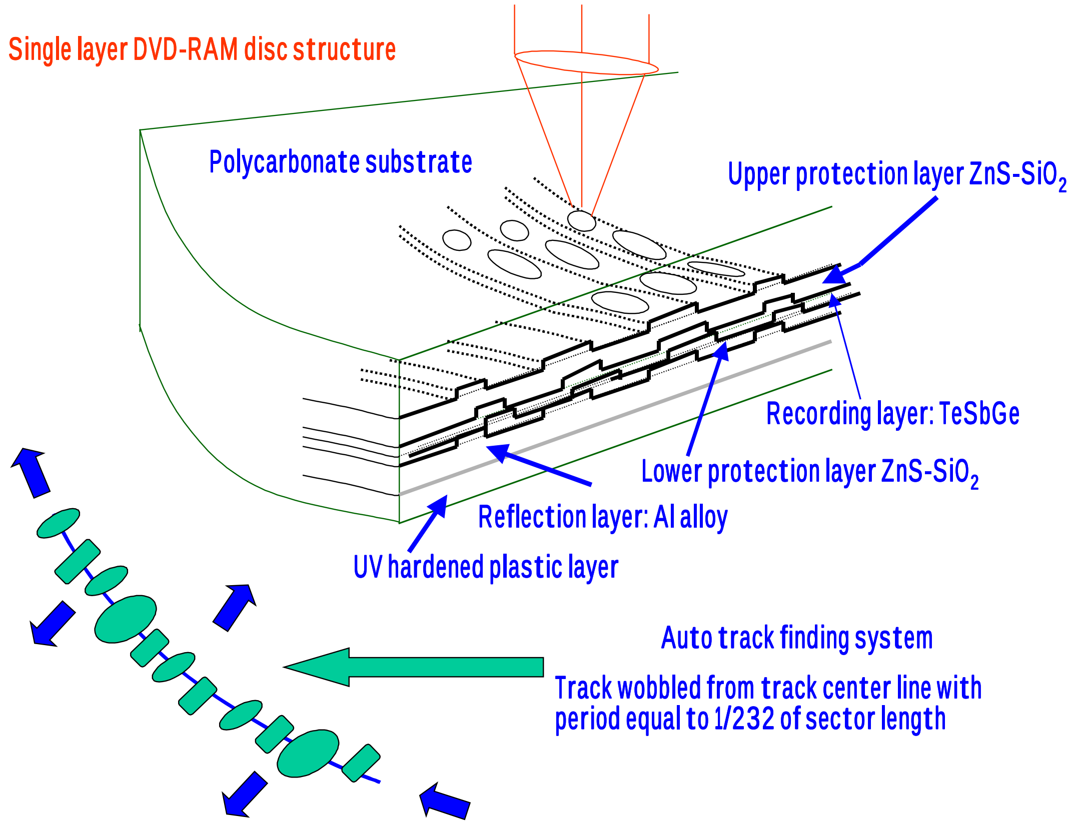


Figure 7. Structure of single-layer Phase Change recordable DVD

The recording layer is sandwiched in between dielectric layers for protection. The protection layer material, such as Zinc Sulfide-Silicon Dioxide, ZnS-SiO_2, has a significantly higher melting temperature, and it stays in amorphous state during the entire recording process. The dielectric layers not only protect the recording layer during heating cycles to maintain its thickness constant, but they also improve the reflectivity change between states. This function is sometimes referred to as *optical tuning*.

Optimization of the disc construction, including the alloy composition and thickness of each layer, is an art of compromise.

For rapid heating during the initial record cycle, the record layer should hold all the heat within, but on the transition to amorphous state, the actual recording, quick heat dissipation is required. Slower rate of cooling could form crystals within the amorphous region, which is highly undesirable.

The process of returning to crystalline phase of non-recorded state is even more complex because the crystallization process for the material requires a defined rate of cooling, expressed as 10X degrees per second.

Lateral flow of the molten record layer material degrades the integrity of recorded information. Excessive pressure from the protection layers could cause this undesirable effect. Small amount of high melting temperature material in the record layer, which acts as an agent for lateral flow prevention, is a technique used by some of the media producers.

The structure shown in Fig.7 also illustrates the concept of land-groove recording, which offers two-for-one track pitch reduction. The land-groove recording does not have the inter track guard band for reduction/elimination of the data cross talks between tracks.

By making the elevation difference between the land and the groove to be exactly ¼ wavelength of the read laser wavelength, however, the signals from adjacent tracks picked up by the skirt energy of the read beam cancel by themselves. This technique is just as effective as the guard-band-less, azimuth recording used in high density magnetic tape recording.

DVD RAM

The DVD-RAM is a recording format intended for all data storage applications, including imagery, video, and numerical data. The first product, with 2.6 GB per surface capacity, was introduced in 1998. The 2.6 GB disc surface, as shown in Fig.8, is divided into two areas. In the central, non-recordable area, format and product information is stored. The outer area, where data is to be written, operates as a phase-change recording disc. The recordable area is divided into 24 concentric zones, zone-0 through zone 23. Each zone consists of 944 land tracks and 944 groove tracks.

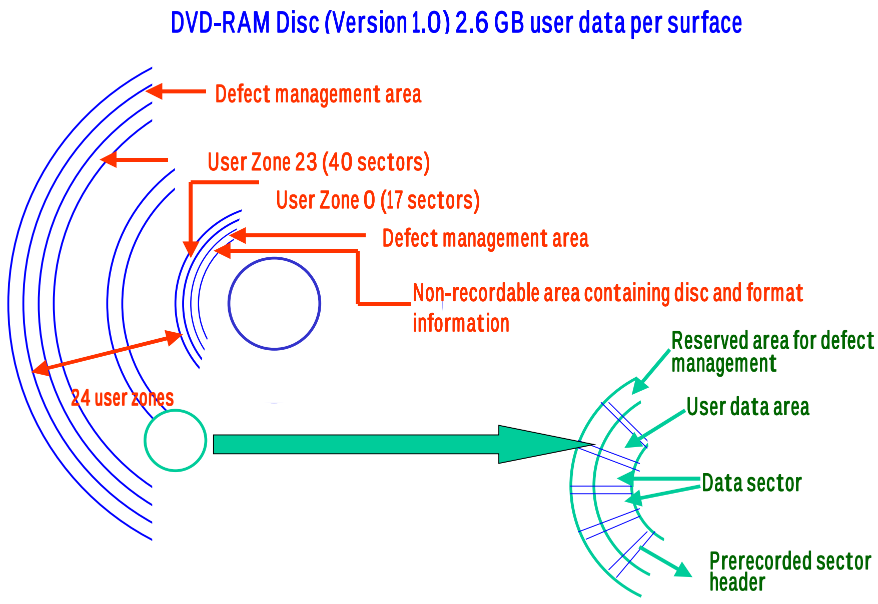


Figure 8. DVD-RAM version 1.0

To maintain near constant data recording density throughout the disc surface, more data is recorded in outer zones than in the inner zones. This is accomplished by recording varying number of data sectors - - each sector has 2 KB user data - - in each zone. The inner most zone holds 17 sectors. One sector is added to each zone as the zone moves outward, and the outer most zone holds 40 sectors. This technique is referred to as ZCLV, Zone Constant Linear Velocity recording. The head-to-medium velocity is essentially constant at 6.0 meters/sec.

Each zone contains areas normally used for data storage and reserved areas to be used as replacement for defective user blocks. Defect area replacement is done on a sector basis, and it is automatically accomplished by the Defect Sector Management, DSM, operation.

The operational instructions, and data related to defect area replacement, are stored in the inner- and outer-most portion of the disc, as shown in Fig. 8.

In addition to the land-and-groove recording, DVD-RAM employs a technique which significantly improves the in-track density - mark edge recording. In conventional optical recording, as shown in Fig. 9 A, 1 is recorded as a mark, or pit, on the medium.

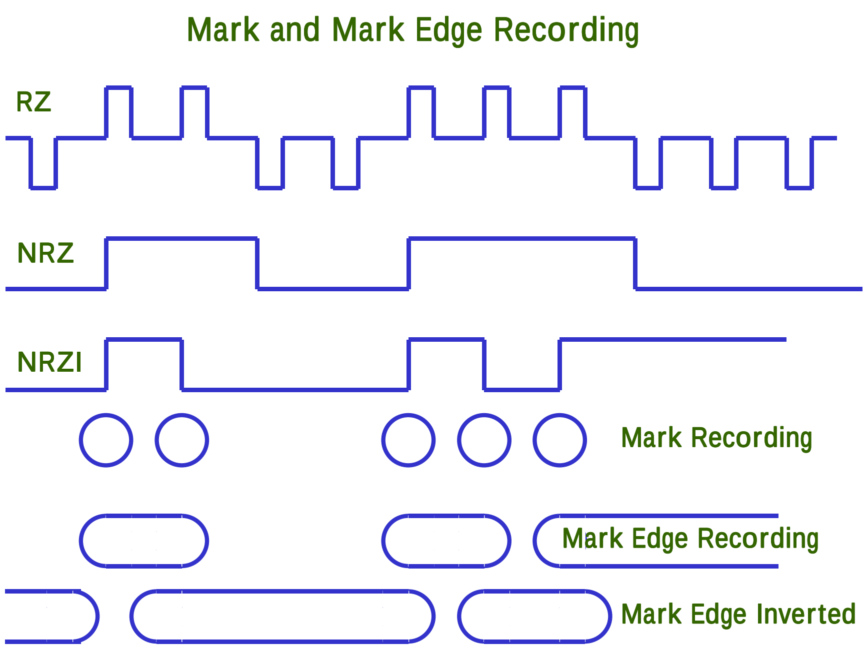


Figure 9. Mark edge recording

In a consecutive run of 1's, the successive recording of pits tends to raise the local medium temperature higher, and unless carefully controlled, the pits recorded get successively larger. This phenomenon, coupled with the fact that pits are closely placed to begin with, makes the minimum bit spacing longer than what is dictated by the actual bit size itself.

Mark edge recording offers an attractive solution for this problem. In mark edge recording, the consecutive 1's are recorded as an elongated pit, each edge corresponding to the start and end of the consecutive 1's. This technique makes it unnecessary to record a short pit, enabling the system to record a significantly higher amount of data within the given physical media length.

The 2.6 GB DVD-RAM media is available in Single Side version as well as in Double Sided version. Unlike the DVD-Video Dual layer disc, Double sided DVD-RAM must be turned over to write and read both sides by a writer/reader drive. Both layers within a DVD-Video dual layer disc are readable by a standard DVD player without reinserting the disc.

Specifications for the higher capacity version DVD-RAM, with per surface capacity of 4.7 GB, have been finalized.

Version 2.0 of the specifications for the 4.7 GB disc, state the following characteristics:

Track Pitch = 0.615 μm, Minimum mark Length = 0.28 μm
No. of Zones = 35
Number of Sectors in innermost zone = 25
Number of Sectors in outermost zone = 59

The 4.7 GB capacity disc is expected to be available in both single sided (4.7 GB) and double sided (9.4 GB) versions.

The data transfer rate for the high capacity version is twice that of the 2.6 GB version, at 2.76 MB/sec. This is the sustainable record rate of the system. As in the case for CD-ROM, a DVD-RAM disc can be read at a much faster rate than its record rate.

Specifications for the recordable DVD's are shown in Fig. 10.

	Version 1.0	Version 2.0	Future
Year of introduction	1998	1999	2002
Capacity per surface, GB	2.6	4.7	12~18
Double sided media	Yes	Yes	Likely
Laser /nm	650	650	450
Objective lens NA	0.6	0.6	0.8~0.85
Track pitch μm	0.74	0.615	0.3
Minimum mark length μm	0.409	0.28	0.2
Max Transfer rate, MB/s	1.38	2.76	6~9

Figure 10. DVD-RAM specifications

DVD Capability Expansion Possibilities

DVD proponents faced the age-old dilemma of designers: when to stop enegineering development and finalize the specifications. The technology was on a steep ascending curve then, and the disc data holding capacity was growing daily

Areal Density Improvement

Today, they were facing exactly the same problem. The blue/Violet light diode laser in 400 nanometer wavelength region is no longer a laboratory curiosity. While the price is quite steep, a manufacturer is delivering a 405 nanometer laser based on Gallium Nitride Crystal with 10 mw CW capability, and guaranteeing 10,000 hours operation under room temperature. A score of other semiconductor manufacturers are all developing a laser of similar performance and capability. The major supplier of current CD and DVD laser established a two year project to complete the development of their short wavelength laser.

Another component requiring up-grades to increase the areal density is the objective lens. In this area also, experimental lenses approaching the theoretical limit of unity, in the region of 0.8 to 0.9, have been produced.

Combining a blue/violet laser and a super fast objective lens, an areal density increase of 3 to 5 is practical, making the per surface data capacity to be 15 to 25 GB. A number of 15 to 25 GB experimental disc systems have been demonstrated within the last two years.

Multiple layer Recording

While it is practical to read a dual-layered, embossed pattern DVD-Video disc from its front side, writing to and reading data from a multi layered disc from its front side creates an entirely new set of problems.

Taking a double layer disc as an example, the first and the closest to the front surface record layer must be transparent enough so that the record and play back beams for the second layer can penetrate it without undue attenuation. In case of the playback beam for the second layer, it must pass through the first layer twice.

Also, if the reflective layer for the first recording layer is retained, it must be at least semi-transparent.

Therefore, the multi-layer recording disc must have an entirely different layering structure. A possible structure of dual layer, phase change recording disc is shown in Fig. 12.

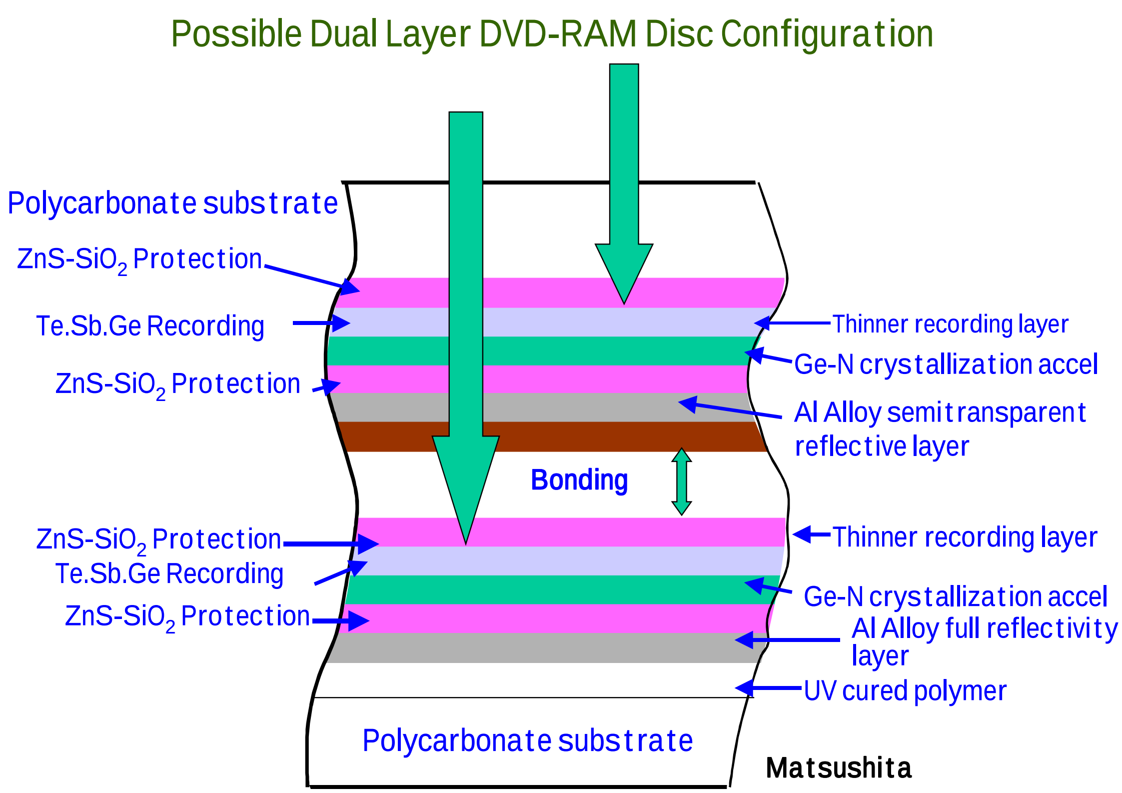


Figure 12. Possible Dual Layer DVD-RAM

Faster Recording Rate

One of the weakness of the phase change recording is its relatively slow recording rate. In version 2.0 of DVD-RAM, it has just reached about 3 MB/sec.

An anticipated application of DVD-RAM is the broadcast video recording camera, the professional camcorder equipment. While 3 MB/sec may be just sufficient for the standard definition television recording, it is entirely inadequate for HDTV applications, where 6 to 12 MB/sec recording rate is required.

As mentioned earlier, the recording rate is essentially governed by the crystallization rate of the recording layer material. In addition to thickness variation and optimization of composition, studies are being conducted to accelerate crystallization by placing an *augmentation* layer next to the recording layer. On the reading side, all DVD discs are already readable at 10 MB/sec, and within three years, technologies will be available to read the disc at rates as fast as 40 MB/sec.

Summary

The entire DVD infrastructure is being driven by the large commercial business. Continuing technology advances are assured because of the rapidly growing markets demanding higher performance and feature-packed products.

DVD-RAM is an attractive data storage technology, offering a high data capacity per unit volume, with expected storage life of 60 years or longer. It could potentially displace magnetic tape in certain applications.

Magneto-Optical recording, while making steady progress in data storage density, is used in the data storage area only, lacking the support enjoyed by DVD from the consumer industry. It can record faster than DVD, and is certain to maintain its place in the overall data storage infrastructure.

Write-once technology, represented by CD-R and DVD-R, is developing a unique position in both private life and business environs. It is a replacement for paper-based notebooks, log books, ledgers, and a convenient and low cost storage for music and pictures.