White Paper
Blu-ray Disc™ Format

1.C Physical Format Specifications for BD-ROM

9th Edition

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NOTICE
For any further explanation of the contents of this document, or in case of any perceived inconsistency or ambiguity of interpretation, please consult with:

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1. Introduction

Blu-ray Disc™ Read-Only format Part 1 (Physical format) is realized by using many technologies so as to achieve high capacity, high data transfer rate, reliable data reading, etc. In this White Paper we introduce the key technologies underlying BD-ROM Part 1.

Blu-ray Disc Association (BDA) has released 25GB/50GB BD-ROM format Part 1 (version 1.0) in 2004. Additionally, BDA has released 50GB/66GB/100GB BD-ROM Ultra HD Blu-ray™ format Part 1 (version 2.0) in 2015.

The basic features of 25GB/50GB BD-ROM (version 1.0) and Ultra HD Blu-ray™ (version 2.0) are explained in Chapter 2 and Chapter 3, respectively.

Chapters 4 to 17 are common technologies for both 25GB/50GB BD-ROM and Ultra HD Blu-ray™.

In Chapter 4 the fundamental attributes contributing to the high capacity of BD-ROM are explained.

In Chapter 5 items related to disc structure are explained, such as the 0.1 mm thick Cover Layer and 1.1 mm thick Substrate. How the lack of transparency requirement for the 1.1 mm Substrate contributes to reduce the manufacturing cycle time of BD-ROM is explained in clause 5.1. The Cover Layer formation technology is explained in clause 5.2.

BD-ROM was required to be a bare-disc system, so this was a large focus of the effort of the BD-ROM technical working group. In Chapter 6 some key technologies and the test method for the bare disc are explained.

Chapter 7 describes why the reflectivity of BD-ROM is higher than that of BD-RE.

Both concave and convex Pit structures are allowed, which is explained in Chapter 8.

One difference from DVD is that both DPD (Differential-Phase Detection) and Push-Pull for BD-ROM have been specified and they are described in Chapter 9.

The BD family employs 17PP ((1, 7) RLL Parity-Preserve, Prohibit Repeated-Minimum Transition Run-length code) modulation in combination with a Viterbi decoder in order to give wide system-margins. This 17PP modulation is also effective for the BD-ROM disc system and is explained in Chapter 10.

In the case of the CD and DVD formats, the Read-Only ROM specifications were created first, and ROM data were recorded continuously. Thus when Recordable CD-R and DVD-R were developed, the problem of linking of different recordings to make a compatible, continuous recording was a challenge. In Blu-ray Disc™, the Rewritable BD-RE specifications were created, before the BD-ROM specifications, and therefore there was full freedom to define the Linking Area. Chapter 11 describes the BD-ROM data structure including the Linking Frame.

Recorded data density in tangential direction is increased in BD-ROM disc compared with CD/DVD discs. Thus, it is difficult to evaluate the signal quality of the disc by using conventional jitter measurement. In Chapter 12, new signal quality evaluation methods applied to BD-ROM discs are explained.

Disc-manufacturing process such as mastering and replication are explained in Chapter 13.

When considering the storage of Audio or Video contents in BD-ROM discs, it is crucial to also include the possibility of Content-protection technology. Details on Content-protection technology are not discussed in this document.

The BD-ROM specifications include a Source-Identification (SID) code and a Burst-Cutting Area (BCA) similar to what is used already in CD and DVD. SID code and BCA are explained in Chapter 14 and 15 respectively.

The background of RSER measurement is explained in Chapter 16.

The maximum read-power for BD devices is explained in Chapter 17.

2. 25GB/50GB BD-ROM disc (version 1.0)

2.1 General

25GB/50GB BD-ROM format (version 1.0) specifies a disc which has single or two Recorded Layers. Each Recorded Layer has the maximum User Data capacity of 25 GBytes.

The BD-ROM disc uses a Substrate of about 1.1 mm nominal thickness.

In the case of a Single-Layer disc the Substrate is covered with 1 Recorded Layer on top of which a transparent Cover Layer of about 0.1 mm is applied. This disc has the maximum User Data capacity of 25 Gbytes.

In the case of a Dual-Layer disc the Substrate is covered with 2 Recorded Layers separated by a transparent Spacer Layer of about 0.025 mm. The first Recorded Layer seen from the read-out side of the disc is semi-transparent. On top of this first Recorded Layer, a transparent Cover Layer of about 0.075 mm is applied. This disc has the maximum User Data capacity of 50 Gbytes.

All Recorded Layers contain Pits and Spaces that have been recorded during manufacturing of the disc. The Pits and Spaces form Tracks containing User Data and Addresses which serve as a navigation system.

Read-out of the data is accomplished through the Cover Layer or through the total stack of Cover Layer, first Recorded Layer and Spacer Layer, depending on which Recorded Layer is involved.

The disc is intended to be used without a Cartridge. For special applications or for severe environments a Cartridge may be used.

2.2 Disc outline

Fig. 2-1 shows the outline of a Single-Layer BD Read-Only disc and Fig. 2-2 shows the outline of a Dual-Layer BD Read-Only disc. To improve scratch resistance, the Cover Layer can optionally be protected with an additional Hard-coat Layer.

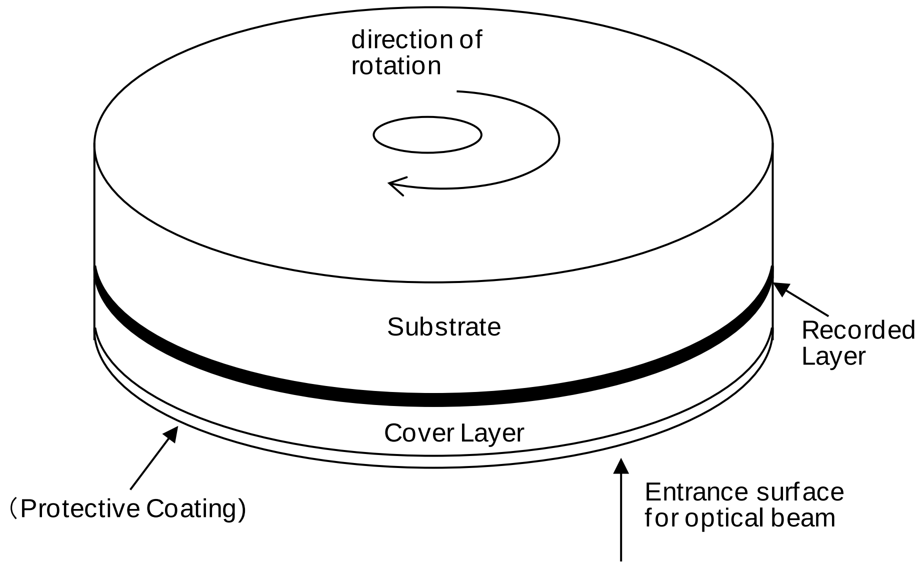


Fig. 2-1 Outline of Single Layer BD Read-Only disc

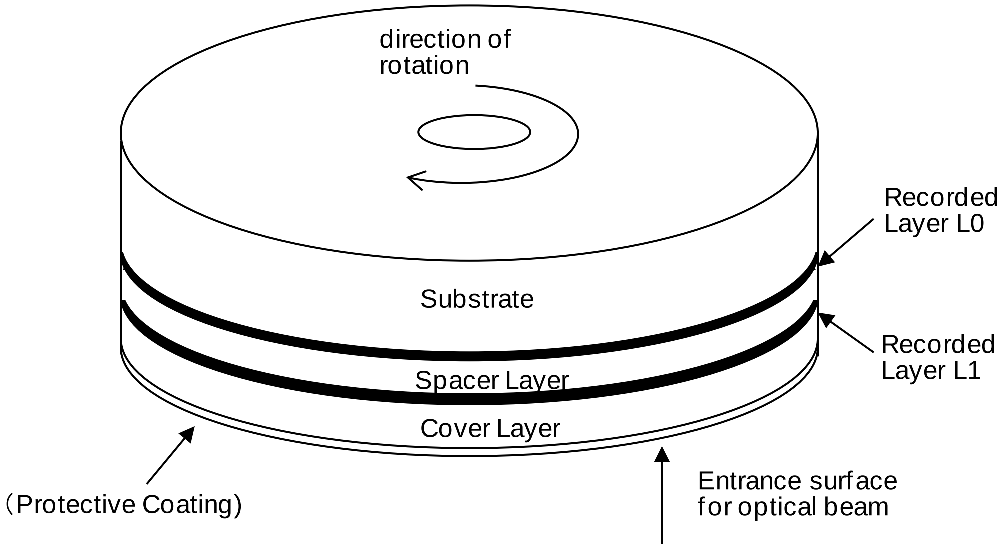


Fig. 2-2 Outline of Dual Layer BD Read-Only disc

2.3 Capacity

BD-RE version 1.0 specifies the capacities of 23.3 GB/layer, 25 GB/layer and 27 GB/layer (Reserved). The 27 GB/layer specifications need further confirmation for mass-production. So the 27 GB specifications are not allowed to be used in the current physical specifications of BD-ROM. In technical conferences such as ISOM (International Symposium on Optical Memory) and ODS (Optical Data Storage), some companies have already reported the possibility of BD-ROM discs. To maintain compatibility with BD-RE version 1.0, we specified 23.3 GB/layer and 25 GB/layer for BD-ROM version 1.0 specifications. Testing was conducted on 23.3 GB and 25 GB Single-Layer discs and 46.6 GB and 50 GB Dual-Layer discs, and the feasibility of concept and mass manufacturing was confirmed.

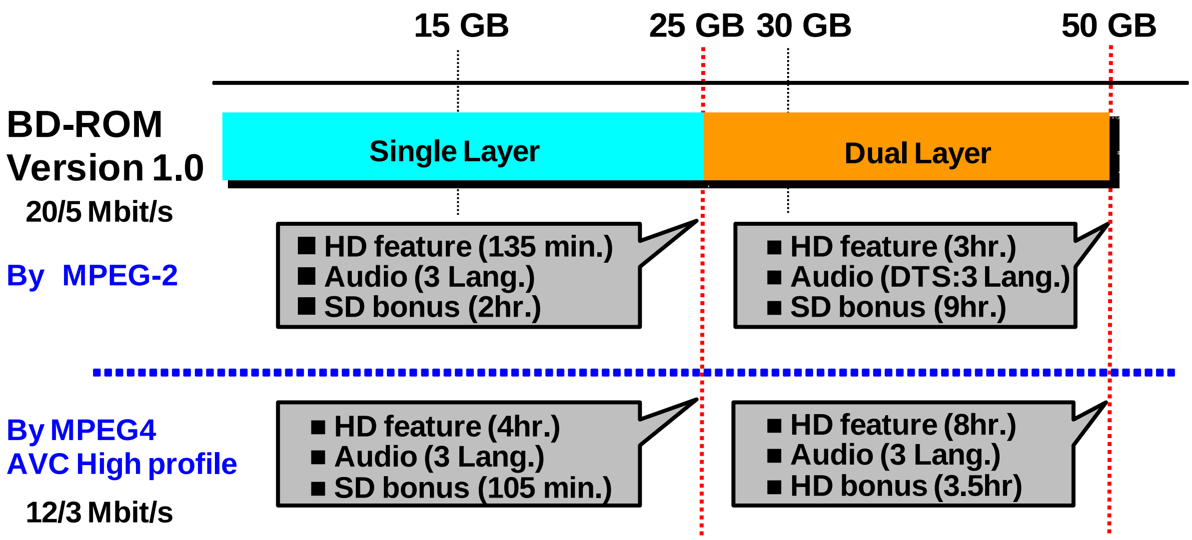


Fig. 2-3 BD-ROM version 1.0 capacity

In Fig. 2-3, most movie applications can be recorded on a Single-Layer disc and we can expect a reasonable cost for such discs. Dual-Layer discs expand the application range even more.

From BD-ROM version 1.3 the lowest capacities of 23.3 GB/46.6 GB were excluded from the specifications. One reason was that the disc-manufacturing technology progressed and the other reason was to reduce the effort for the test procedure and test discs for a drive.

Table 2-1 shows the Channel-bit length and maximum capacities of BD-ROM.

Main parameters	
Channel-bit length	74.50 nm
Data-bit length	111.75 nm
Reference Velocity (1X)	4.917 m/s
Maximum User-Data capacity Single Layer Dual Layer	 25.025 Gbytes 50.050 Gbytes

Table 2-1 Channel-bit length and maximum capacities

2.4 Data rate

For high-definition movies a much higher data-rate is needed than for standard definition movies. With the BD format's choices for both NA and wavelength we have been able to realize a format with 5X higher data-rate while only doubling the rotation rate of DVD-ROM discs.

The following numbers offer a comparison:

Data-bit length: 111.75 nm (25 GB) (267 nm for DVD)
Linear Velocity: 7.367 m/s (Movie application) (3.49 m/s for DVD).
Minimum User-Data transfer rate: 54 Mbit/s (2D Movie application, max. TS rate: 48 Mbit/s)
72 Mbit/s (3D Movie application, max. TS rate: 64 Mbit/s)
(11.08 Mbit/s for DVD)

The BD system has the potential for future higher-speed drives.

TS (Transport Stream) rate

The BD video player shown in Fig. 2-4 has a buffer. The maximum TS rate is the maximum rate at which the content of the buffer has to be transferred to the decoder. If the minimum User-Data transfer rate from the disc to the buffer- i.e. the input rate into the buffer – is higher than the specified maximum TS rate – i.e. the output rate from the buffer – then after some time, the buffer is filled. The pick-up head stops reading, using jump back mode, until the data content of the buffer is decreased. Thus the video player can be seen as a kind of asynchronous system.

In order to ensure a seamless reproduction, the User-Data transfer rate should be larger than the maximum TS rate.

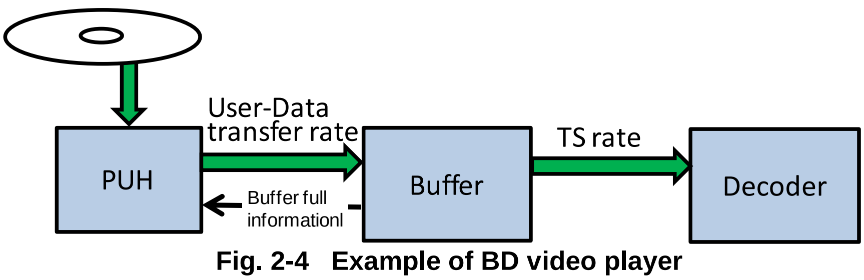


Fig. 2-4 Example of BD video player

2.5 Main parameters

In this clause, representative parameters of 25/50GB disc are shown.

Disc Structure		
Single-sided disc Both Single-Layer disc(SL) and Dual-Layer disc(DL)		
Recording method		In-pit / On-pit
BCA	[mm radius]	21.0 to 22.2
Lead-in Area	[mm radius]	22.0 to 24.0
Data Area	[mm radius]	24.0 to 58.0
Scratch resistance		Taber abrasion test
Capacity related items		
Total capacity SL (DL)	[GB]	25.0 (50.0)
User-bit rate	[Mbit/s]	35.965
Channel-bit rate	[Mbit/s]	66.000
Shortest-Pit length	[nm]	149.0
Linear Velocity @ 1x	[m/s]	4.917
Track Pitch	[μm]	0.32
Measuring condition		
Wave length (λ) of laser beam	[nm]	405 ± 5
NA		0.85 ± 0.01
Polarization		circular
Rim intensity		
Radial	[%]	60 ± 5
Tangential	[%]	65 ± 5
Wave front aberration	[λrms]	0.033 max.
Relative-intensity-noise of laser		-125 dB/Hz max.
Normalized detector-size	[μm^2]	$S/M^2 \leq 25$
Read power	[mW]	0.35 ± 0.1
Mechanical parameters		
Radial tracking		
Runout SL and DL	[μm]	75 pp max.
LF residual-error (SL)	[nm]	9 max.
HF residual-error(SL)	[nm]	6.4 rms max.
Axial tracking		
Runout [mm]		0.3 max.
LF residual-error	[nm]	45 max.
HF residual-error	[nm]	32 rms max.
Disc thickness	[mm]	0.9 to 1.4
Disc mass	[g]	12 to 17
Disc imbalance	[gmm]	≤ 4.0
Disc radial-tilt (α angle)	[◦]	1.60 pp max.
Disc tangential-tilt (α angle)	[◦]	0.60 pp max.

Optical parameters		
Cover Layer		
Thickness (SL)	[µm]	100 ± 5
Thickness (DL)	[µm]	75 ± 5
Thickness variation	[µm]	≤ 3.0
Spacer Layer		
Thickness (DL)	[µm]	25 ± 5
Thickness-variation including Cover Layer (DL)	[µm]	≤ 3.0
Substrate		No requirement
Reflectivity SL	[%]	35 to 70 / 12 to 28
Reflectivity DL	[%]	12 to 28
In-plane birefringence	$[\Delta n_{//}]$	$\le 1.5*10^{-4}$
Perpendicular birefringence	$[\Delta n_{\perp}]$	$\le 1.2*10^{-3}$
Refractive index		1.45 to 1.70
Operational signals		
Limit Equalizer Jitter	[%]	
SL disc		≤ 6.5
DL Layer L0		≤ 6.5
DL Layer L1		≤ 8.5
Symbol Error Rate without defects		$< 2 \times 10^{-4}$
Defect size (black dot with birefringence)	[µm]	< 300
Asymmetry		-0.10 to +0.15
DPD		0.28 to 0.62
Push-Pull		0.10 to 0.35
Track cross		≥ 0.10

2.6 Hybrid disc

Hybrid discs within BD families such as the Dual-Layer discs with the combination of BD-ROM Layer and BD-R Layer can be considered. The feasibility of this type of Hybrid discs, which is called as Intra-Hybrid disc, still has to be confirmed by the BDA. Therefore, the Intra-Hybrid discs are not allowed in the current physical specifications of BD-ROM.

Hybrid discs with the combination of BD-ROM Layer and other-type layer such as DVD-ROM Layer or CD-ROM Layer are also possible. This ROM-ROM type Hybrid disc combination is defined in the BD Hybrid disc specifications. Fig. 2-5 shows the examples of ROM-ROM type Hybrid discs. At the 0.1 mm depth from the surface there is BD-ROM Layer. The DVD-ROM Layer is located at 0.6 mm depth and the CD-ROM Layer at 1.2 mm depth. These layers can be read from one side of a disc. The CD-ROM and DVD-ROM Layers should satisfy the relevant specifications (ISO/IEC 10149, ISO/IEC 16448/16449) so that legacy players can recognize and read these layers as CD-ROM and DVD-ROM. However, the readability of the CD and DVD Layers does not only depend on the quality or conformance of the CD and DVD Layers itself. Another condition is that the BD-ROM Layer(s) should be almost transparent at the wavelength of 780 nm or 650 nm. On the other hand BD-ROM Layer(s) should have enough reflectivity at 405 nm. In order to realize this requirement, the low-reflectivity range of 12-28 % is allowed for a Single-Layer BD-ROM.

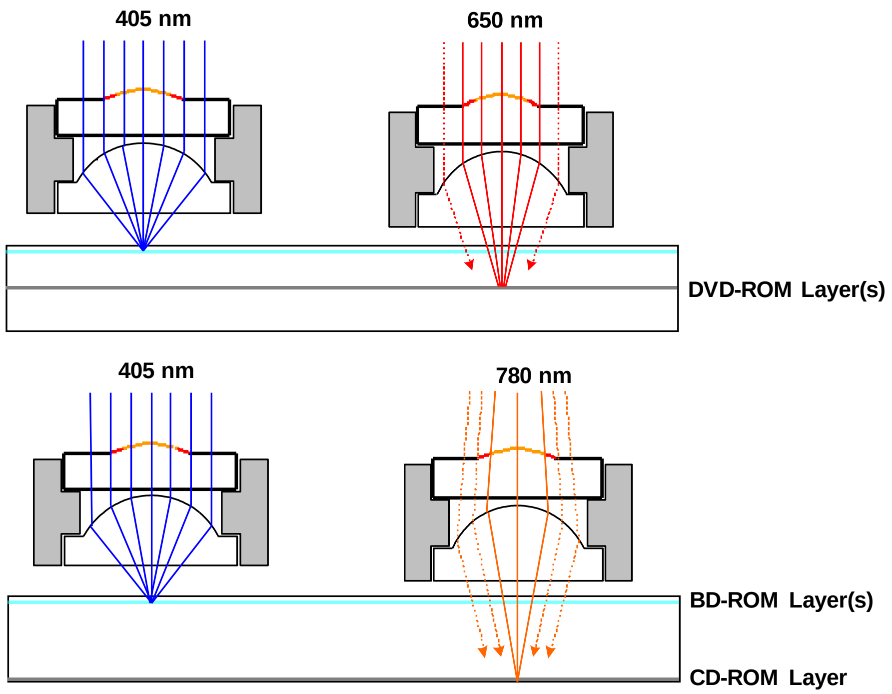


Fig. 2-5 Examples of ROM-ROM type Hybrid discs

There is a possibility for BD/DVD/CD compatible drives that they first focus in DVD-ROM or CD-ROM Layer of a Hybrid disc and never going to read BD-ROM Layer. In order to prevent such a problem, the Hybrid-disc information (existence of DVD-ROM or CD-ROM Layer) is recorded in the Disc-Information in PIC Zone and copied to the optional BCA. A drive is recommended to read such Disc-Information of Layer L0 (either in PIC Zone or BCA or both) at the start up procedure.

3. Ultra HD Blu-ray™ (version 2.0)

3.1 General

The Ultra HD Blu-ray™ format defines the discs which have the maximum User Data capacity of 50 Gbytes, 66 Gbytes and 100 Gbytes.

The Ultra HD Blu-ray™ disc uses a Substrate of about 1.1 mm nominal thickness.

In the case of 50GB disc the disc structure is the same as the 50GB disc which is defined in 25GB/50GB BD-ROM format (version 1.0). But 50GB Ultra HD Blu-ray™ disc cannot be played back by the players designed with 25GB/50GB BD-ROM format (version 1.0) because of incompatibility of video coding method, content protection system, Disc Information, etc..

In the case of 66GB disc the Substrate is covered with two Recorded Layers separated by a transparent Spacer Layer of about 0.025 mm. The first Recorded Layer seen from the read-out side of the disc is semi-transparent. On top of this first Recorded Layer, a transparent Cover Layer of about 0.075 mm is applied. Each Recorded Layer has the maximum User Data capacity of 33.4 Gbytes. In total, this disc has the maximum User Data capacity of 66.7 Gbytes.

In the case of 100GB disc the Substrate is covered with three Recorded Layers separated by transparent Spacer Layers of about 0.025 mm and 0.018 mm. The first and second Recorded Layers seen from the read-out side of the disc are semi-transparent. On top of the first Recorded Layer, a transparent Cover Layer of about 0.057 mm is applied. Each Recorded Layer has the maximum User Data capacity of 33.4 Gbytes. In total, this disc has the maximum User Data capacity of 100 Gbytes.

All Recorded Layers contain Pits and Spaces that have been recorded during manufacturing of the disc. The Pits and Spaces form Tracks containing User Data and Addresses which serve as a navigation system.

Read-out of the data is accomplished through the Cover Layer or through the total stack of Cover Layer, Recorded Layer(s) and Spacer Layer(s), depending on which Recorded Layer is involved. The different maximum capacities of the Recorded Layers are realized by changing the “in-Track” or tangential density.

The disc is intended to be used without a Cartridge.

3.2 Disc outline

Fig. 3-1 shows the outline of a Dual-Layer BD Read-Only disc and Fig. 3-2 shows the outline of a Triple-Layer BD Read-Only disc. To improve scratch resistance, the Cover Layer can optionally be protected with an additional Hard-coat Layer.

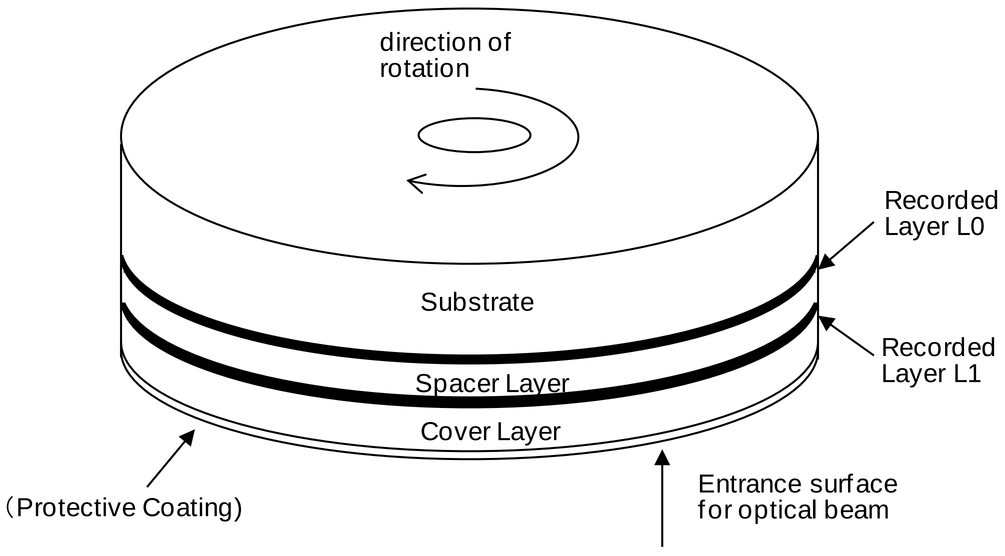


Fig. 3-1 Outline of Dual Layer BD Read-Only disc

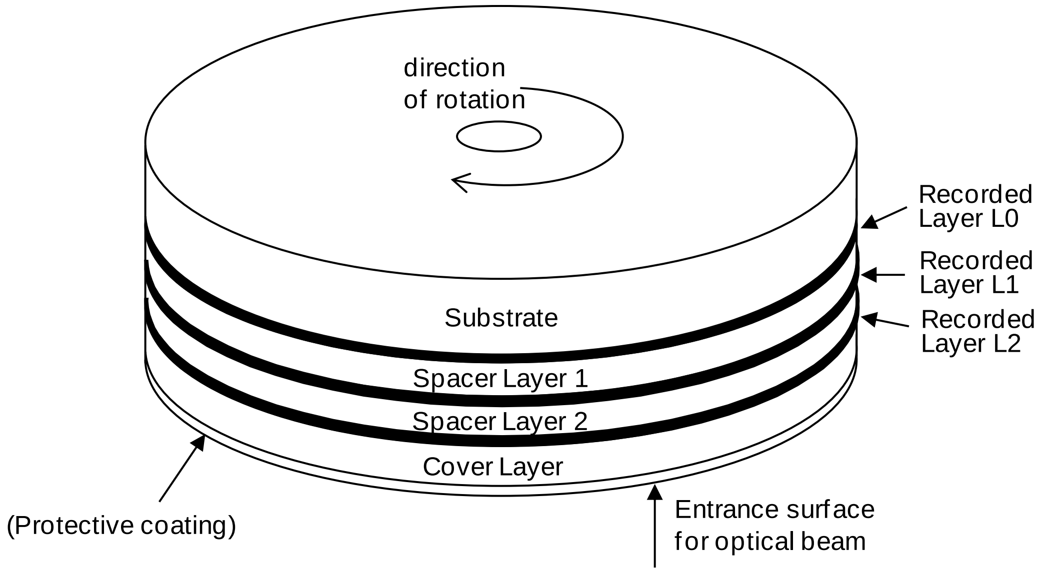


Fig. 3-2 Outline of Triple Layer BD Read-Only disc

3.3 Capacity

The Ultra HD Blu-ray™ format is created for a container of 4K UHD and/or High Dymanic Range(HDR) movies. Disc for 4K UHD and/or HDR movie requires much larger capacity than that for HD movie even if new video coding method(HEVC) is applied.

In the Ultra HD Blu-ray™ format Part 1, three types of discs(50GB/66GB/100GB) are defined.

Each layer in 66GB/100GB disc has the maximum User-Data capacity of 33.4GB. The disc with 33.4GB per layer has already been defined in the BDXL™ R/RE specifications. By applying the BDXL technologies, we have achieved the BD-ROM discs with large capacity and high transfer rate.

50GB Ultra HD Blu-ray disc can be used for the content not requiring such a high capacity. 50GB Ultra HD Blu-ray™ disc can be manufactured using the same manufacturing system as 50GB BD-ROM for HD content. For manufacturing of 66/100GB BD-ROM discs, new technologies might be necessary.

Fig. 3-3 shows the Channel-bit length and related maximum capacities of Ultra HD Blu-ray™.

Main parameters of Data Zone	50GB disc	66GB disc	100GB disc
Channel-bit length	74.50 nm	55.87 nm	55.87 nm
Data-bit length	111.75 nm	83.81 nm	83.81 nm
Reference Velocity	4.917 m/s	3.688 m/s	3.688 m/s
Number of Recorded Layers	2	2	3
Maximum User-Data capacity	50.050 Gbytes	66.735 Gbytes	100.103 Gbytes

Fig. 3-3 Channel-bit lengths and related maximum capacities

3.4 Data rate

Ultra HD Blu-ray™ movies require higher data transfer rate than HD movies due to increase of data size in each frame. Higher transfer rate is realized by higher disc rotation speed.

But high rotation speed causes increasing an acoustic noise level and a power consumption of spindle motor. In consideration of these issues, we decided to limit the maximum disc rotation speed to 5000 r/min when creating the specifications. The User-Data transfer rate required for the application is specified so as not to exceed the maximum disc rotation speed 5000 r/min.

In the case of 66/100GB discs, recorded data density in tangential direction is increased compared with 50GB discs. Therefore, 66/100GB discs can achieve higher data transfer rate at the same linear velocity.

In the Ultra HD Blu-ray™ format, a Default TR(Transfer Rate), a Low TR Option and a High TR Option are defined (see Fig. 3-4, Fig. 3-5 and refer clause 2.4).

In the Default TR, the maximum TS rate is 109 Mbit/s for 66/100GB discs and 81.7 Mbit/s for 50GB discs. The corresponding minimum User-Data transfer rates are specified as 123 Mbit/s and 92 Mbit/s, respectively. At these transfer rates, the maximum rotation speed of the disc does not exceed 5000 r/min at the innermost part of the Data Zone.

The Low TR Option is defined for the content not requiring such a high data transfer rate. In the Low TR option, the maximum TS rate is limited to 81.7 Mbit/s for 66/100GB disc and to 64 Mbit/s for 50GB discs. The corresponding minimum User-Data transfer rates are specified as 92 Mbit/s and 72 Mbit/s, respectively. The disc rotation speed can be reduced to the speed corresponding to these User-Data transfer rate. Then the acoustic noise caused by disc rotation can be decreased.

The High TR Option is defined for the content requiring higher transfer rate. This option is applied only to 66/100GB discs. In this option, the maximum TS rate can be increased to 127.9 Mbit/s. The corresponding minimum User-Data transfer rate is specified as 144 Mbit/s. But, if the disc is rotated at this transfer rate, the disc rotation speed exceeds 5000 r/min at inner part of the Data Zone. In order to limit the disc rotation speed to 5000 r/min, the Data Zone in each layer is divided into two Zones: an HTR Zone and an LTR Zone. The maximum TS rate of 127.9 Mbit/s is applied only to the HTR Zone, which occupies 92 % of the Data Zone. The LTR Zone is located at the inside of the HTR Zone. The maximum TS rate of the application in the LTR Zone is limited to 109 Mbit/s. This transfer rate is the same as the Default TR.

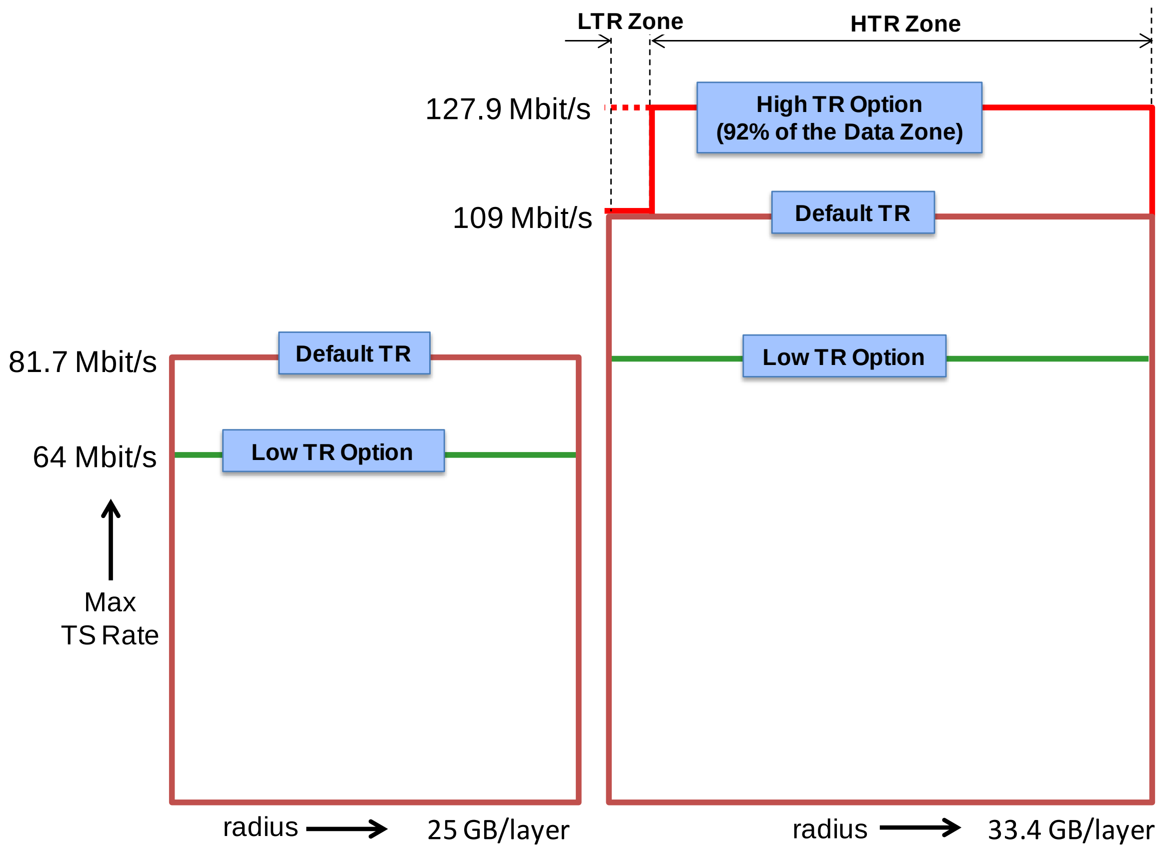


Fig. 3-4 maximum TS rate options

disc	Transfer Rate Option *)	Max TS Rate (Mbit/s)	Min. User-Data transfer rate (Mbit/s)
50GB discs	Low TR Option	64	72
	Default TR	81.7	92
66/100GB discs	Low TR Optioin	81.7	92
	Default TR	109	123
	High TR Option	127.9 **)	144 **)

*) The same TR Option must be applied to all layers of a disc.
**) High TR values apply to the outer 92% of the 33GB layer capacity, while the Default TR values are used for the inner 8% of each layer.

Fig. 3-5 Transfer Rate Options for Ultra HD Blu-ray™ disc

3.5 Main parameters

The main parameters of physical characteristics of 50GB Ultra Blu-ray™ disc are the same as 50GB BD-ROM disc specified in version 1.0. In this clause, the main parameters of physical characteristics of 66GB/100GB Ultra HD Blu-ray™ disc are shown.

Disc Structure	
Single-sided disc Both Dual-Layer disc(DL) and Triple-Layer disc(TL)	
Recording method	In-pit / On-pit
BCA [mm radius]	21.0 to 22.2
Lead-in Area [mm radius]	22.0 to 24.0
Data Area [mm radius]	24.0 to 58.0
Scratch resistance	Taber abrasion test
Capacity related items	
Maximum capacity DL (TL) [GB]	66.7 (100.1)
User-bit rate @ 1x [Mbit/s]	35.965
Channel-bit rate @ 1x [Mbit/s]	66.000
Shortest-Pit length [nm]	111.7
Linear Velocity @ 1x [m/s]	3.687
Track Pitch [µm]	0.32
Measuring condition	
Wave length (λ) of laser beam [nm]	405 ± 5
NA	0.85 ± 0.01
Polarization	circular
Rim intensity	
Radial [%]	60 ± 5
Tangential [%]	65 ± 5
Wave front aberration [λrms]	0.033 max.
Relative-intensity-noise of laser	-125 dB/Hz max.
Normalized detector-size [μm^2]	$S/M^2 \leq 25$
Read power [mW]	DL disc : 0.35 ± 0.1 TL disc : 0.70 ± 0.1

Mechanical parameters		
Radial tracking		
Runout	[µm]	75 pp max.
LF residual-error	[nm]	20 max.
HF residual-error	[nm]	9.2 rms max.
Axial tracking		
Runout	[mm]	0.3 max.
LF residual-error	[nm]	80 max.
HF residual-error	[nm]	32 rms max.
Disc thickness	[mm]	0.9 to 1.4
Disc mass	[g]	12 to 17
Disc unbalance	[gmm]	≤ 4.0
Disc radial-tilt (α angle)	[◦]	1.60 max.
Disc tangential-tilt (α angle)	[◦]	0.60 max.
Optical parameters		
Cover Layer		
Thickness (DL)	[µm]	75 ± 5
Thickness (TL)	[µm]	57 ± 5
Thickness variation	[µm]	≤ 2.5(DL), 2.0(TL)
Spacer Layer		
Thickness (DL)	[µm]	25 ± 5
Thickness (TL)	[µm]	25 ± 5, 18 ± 5
Thickness-variation including Cover Layer	[µm]	≤ 2.5
Substrate		No requirement
Reflectivity DL	[%]	12 to 28
Reflectivity TL	[%]	6 to 14
In-plane birefringence	[$\Delta n_{//}$]	≤ $1.5*10^{-4}$
Perpendicular birefringence	[$\Delta n_{\perp}$]	≤ $1.2*10^{-3}$
Refractive index		1.45 to 1.70
Operational signals		
i-MLSE	[%]	
Layer L0		≤ 11.0
Layer L1		≤ 11.5
Layer L2		≤ 12.0
Symbol Error Rate without defects		< 2×10^{-4}
Defect size (black dot with birefringence)	[µm]	< 300
Asymmetry		-0.10 to +0.15
DPD		0.18 to 0.42
Push-Pull		0.10 to 0.35
Track cross		≥ 0.10

4. Realization of large capacity

Like the BD-RE system, the pick-up head for BD-ROM uses a high numerical aperture (NA) lens of 0.85 and a 405 nm blue laser. In early BD-RE systems the high NA was realized by using 2 lenses in combination. Today many single lenses with working distance larger than 0.5 mm have been developed and even lenses which can be used in DVD/BD compatible pick-ups and CD/DVD/BD compatible pick-ups have been developed.

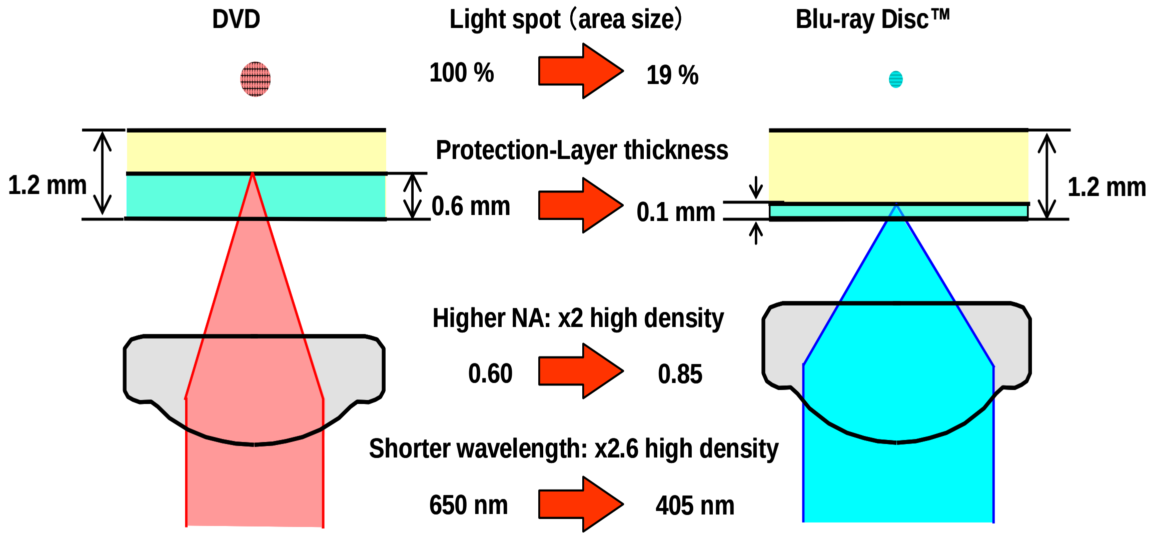


Fig. 4-1 High Capacity contribution

Fig. 4-1 shows that the high-NA lens increases the areal density by 2 times while the blue laser contributes an additional factor of 2.6 times compared to the areal density of DVD. In total, the spot size of Blu-ray Disc™ system is less than 1/5 of the spot size of DVD system, resulting in more than 5 times the capacity of DVD.

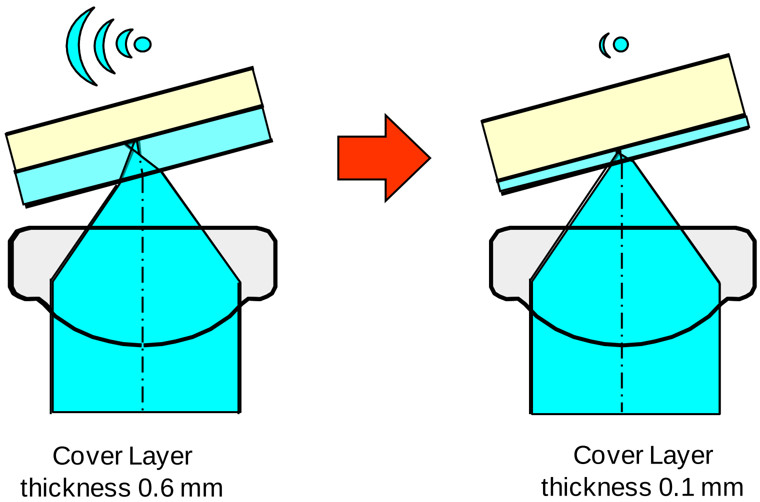


Fig. 4-2 Necessity of 0.1 mm Cover Layer

Fig. 4-2 shows the optical beam degradation due to the disc tilt. This degradation is proportional to NA^3 and the thickness of the Cover Layer. We selected 0.1 mm as the thickness of the Cover Layer, achieving more than ± 1.60 deg (in α angle (see Fig. 4-3)) for the radial tilt margin for BD-ROM, which is similar to that of DVD-ROM.

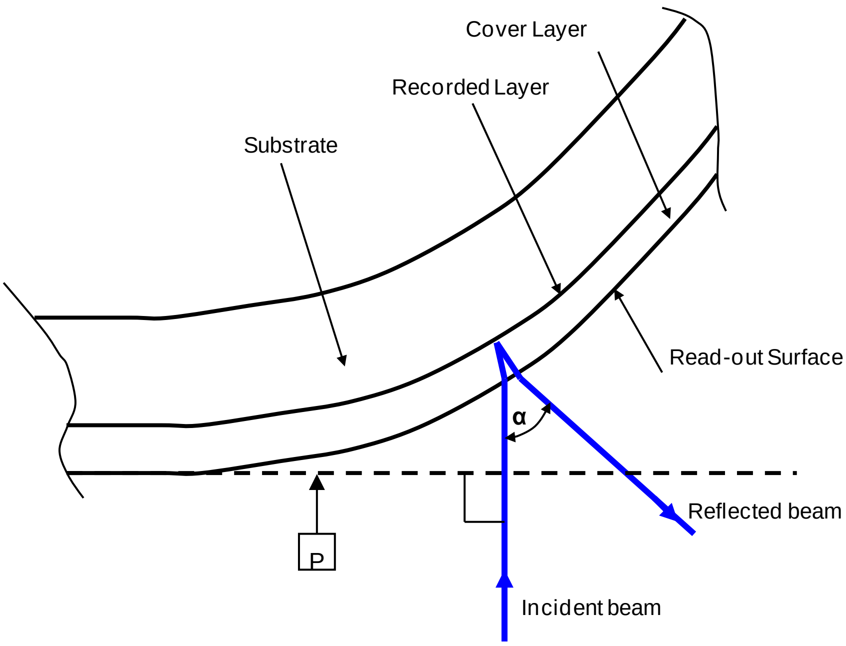


Fig. 4-3 α angle explanation

5. Disc structure

5.1 Advantage of BD substrate

As can be seen in Fig. 2-1, Fig. 2-2, Fig. 3-1 and Fig. 3-2, the optical beam for reading a BD-ROM disc impinges on the Cover Layer and does not go through the Substrate. Therefore the Substrate does not need to be transparent. The Substrate contains the Pits structure and so replication of the Pit pattern is required. But problems of birefringence in the Substrate, which affect the cycle time of the injection molding, are not present.

Fig. 5-1 shows the injection-molding machine. Melted plastic is injected into the mold cavity and the Pit pattern of the stamper is replicated to the plastic by the pressure applied to the mold. If the temperature of the mold is low, the melted plastic becomes rigid near the surface of the mold resulting that several Skin Layers of the plastic are made near the surface of the Substrate, causing birefringence.

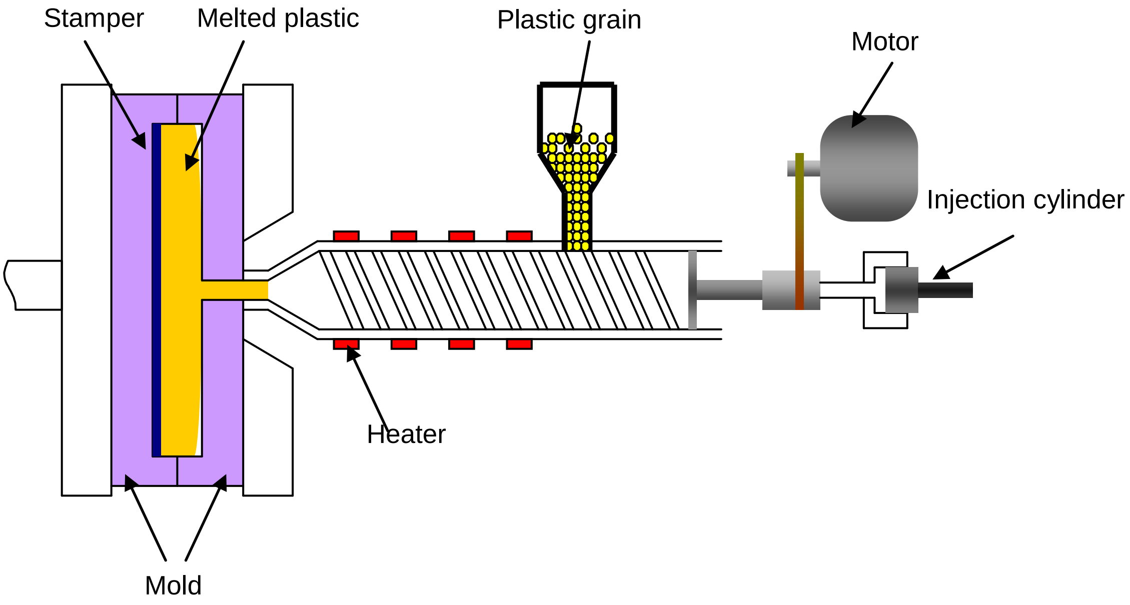


Fig. 5-1 Configuration of Injection mold machine

Fig. 5-2 shows this mechanism of birefringence formation. In order to prevent birefringence, the mold temperature must be kept high during plastic injection. After cooling the Substrate inside the mold so that it becomes rigid and no additional bending will occur, the Substrate is removed from the mold. In order to prevent birefringence a high mold-temperature, followed by a long cooling-time, is required.

Since the read-out of the BD-ROM data is done through the Cover Layer of the disc, the optical characteristics of the substrate are not relevant hence the birefringence problem does not exist for BD-ROM discs. This advantage will allow for a reduced cycle time for the replication process. Since the BD format does not have to consider the optical transparency of the Substrate material, enabling a wide choice of easily moldable plastics (or even paper). By comparison, any format requiring an injection-molding process aiming for low birefringence requires a long cycle-time. The short wavelength of the blue laser makes formats with these requirements even more susceptible to birefringence.

Avoiding these issues is a clear benefit of the BD-ROM approach.

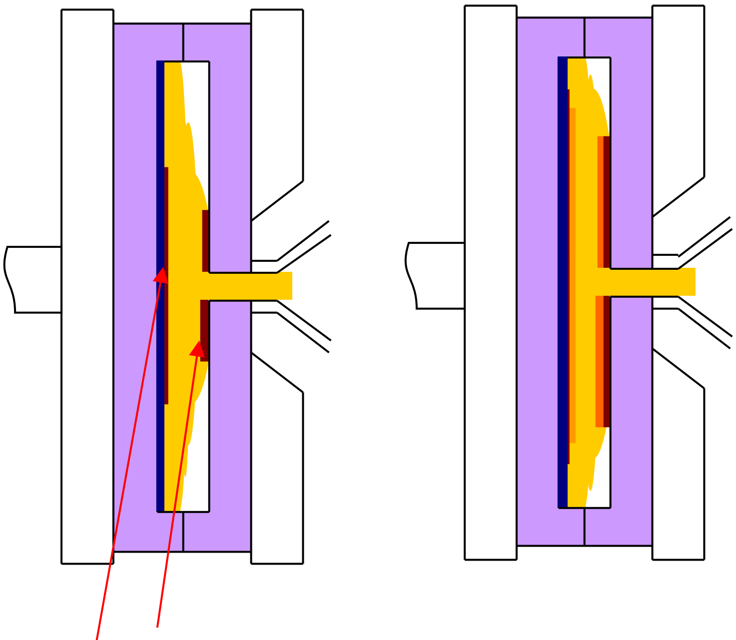


Fig. 5-2 Mechanism of the birefringence formation

5.2 Method to form Cover Layer

During the early development stage of Blu-ray™ Rewritable disc, two different methods were studied to form the 0.1 mm thick Cover Layer of the disc. One was to transfer the data pattern to a 0.1-mm-thick base material and then bond a 1.1-mm-thick Substrate to the base material. The other is to transfer the pattern to a 1.1-mm-thick Substrate by injection molding and then bond a 100 μm-thick Cover Layer to the Substrate. For use in the former method, various pattern-transfer techniques were studied, such as injection molding, and sheet transfer. However, the study revealed that the former method had various problems to overcome: difficulties in transfer itself and in handling the post-processes, such as lamination of the pattern-transferred sheet or base material molded into the sheet, formation of layers, and bonding. On the other hand, the latter method, in which a Cover Layer is bonded to the 1.1-mm-thick Substrate, also had a challenge: the Recording Layer or Reflective Layer is formed on the opposite side from that of the conventional optical disc. However, due to optimization of the Groove or Pit configuration and development of suitable Recording Layer materials, Cover-Layer formation by the latter method has become relatively easy. The Blu-ray Disc™ Cover Layer is mainly produced by the latter method at present and is used for BD-ROM discs also.

The Cover-Layer formation techniques can be divided roughly into two groups. One is to form a 100 μm thick layer on the Substrate using an ultraviolet-curing resin (hereafter referred to as the “UV resin”), similar to that employed as the Protective Layer of CD and as an adhesive in DVD. The other is to bond a Cover-Layer sheet to the Substrate.

Fig. 5-3 shows the basic process for each of these techniques: from upper to lower, forming the entire Cover Layer using a UV resin (Resin-Coating Process), bonding a Cover-Layer sheet using a UV resin, and bonding a Cover-Layer sheet using a Pressure-Sensitive Adhesive (PSA). A Cover-Layer formation difficulty arises from the low Cover-Layer thickness of 100 μm and the thickness-error requirement of ±3 μm. The thickness precision depends on the resin application precision, manufacturing technique, and the thickness of the sheet and Adhesive Layer. The Resin-Coating Process has two challenges: unevenness of resin thickness at the inner and outer peripheries, and resin upheaval on the outer-peripheral area due to surface tension. We have overcome these problems by placing a Center Cap over the Center hole, irradiating the resin coat with UV light while spinning the Substrate, improving the Substrate shape, and so on.

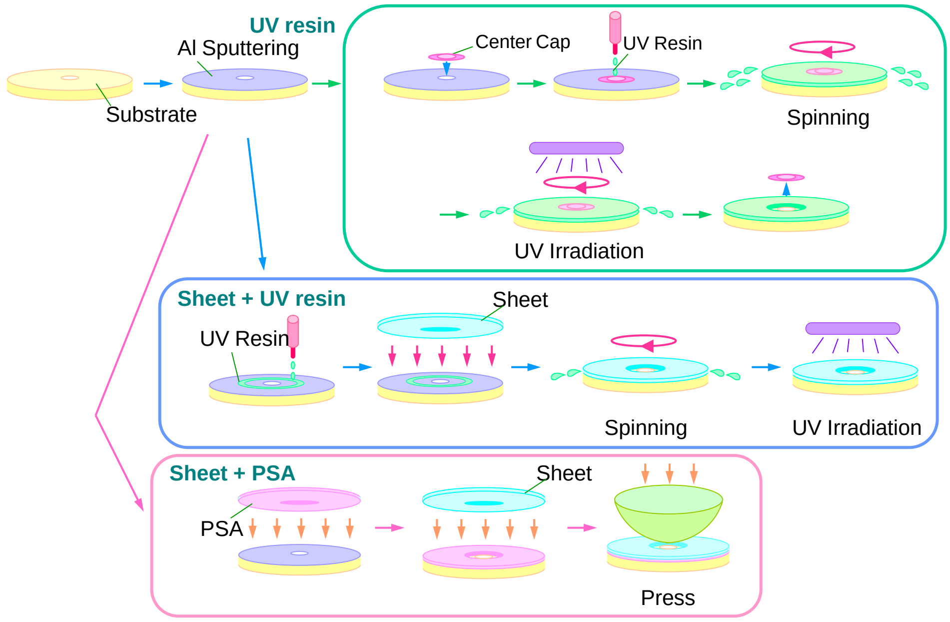


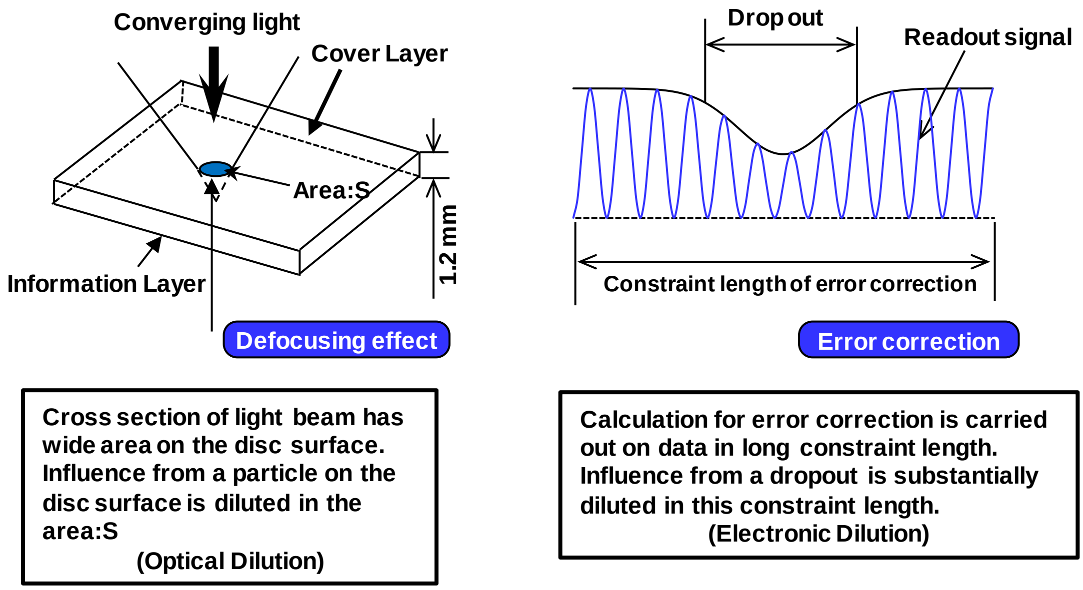
Fig. 5-3 Cover Layer process

6. Bare disc

In order to realize a bare disc system for the 0.1 mm Cover-Layer disc, significant robustness against dust, defects, scratches and fingerprints is required. Error-Correction Code (ECC) is the key technology for reading data. For stable system-operation, servo stability is the key issue. To wipe out fingerprints a hard disc surface is required and a test method for hardness is necessary. These key technologies are explained in this chapter.

6.1 Strong Error-Correction Code (ECC)

It has been regarded that one of principal advantages of optical discs is that the influence of dust or fingerprints on the disc surface is limited because the optical beam is defocused for dust or fingerprints on the surface of the Cover Layer when information is recorded and read. When the Cover-Layer thickness is reduced, the NA value of objective lens can easily be increased, and this defocus effect is sacrificed. Since the Cover-Layer thickness required for the defocus effect is different for digital and analog recordings, a reexamination was needed.



Cover Layer has a function of optically diluting influence from particle on the disc surface. Error correction has a function of electronically diluting influence from a dropout. Both of these functions are similar to each other.

Fig. 6-1 Optical and Electronic Dilution of burst error

The defocusing effect when light passes through the Cover Layer means that by increasing the cross section of incoming laser beam on the Surface Layer, the influence of small dust or fingerprints is diluted within the large cross-section area of the beam. In other words, although the area influenced by dust or fingerprints is enlarged to the size of the light beam, the signal deterioration is reduced and reading errors are prevented. On the other hand, what we call Error Correction is generally used as a means to remove reading errors. During this operation, some redundancy data calculated from a large block of data is attached to the block as error-check data. After the block is read, the check data is inversely calculated to correct partial errors. This can be compared to an image modification process where a partial defect of a photograph is corrected through estimations using adjacent image-data. Through this method, errors are prevented by diluting the influence of partial signal defects in a large-scale data block. It can be said that this Error-Correction method is the electronic version of defocusing by the Cover Layer. This further suggests that defocusing by the Cover Layer partially can be compensated by Error Correction (Fig. 6-1).

Fig. 6-2 shows the comparison of a BD ECC-Block and a DVD ECC-Block, which is applied to 0.1 mm Cover-Layer disc. In the figure 30 µm size defects and 138 µm beam spot size, which corresponds to the spot size on the Cover Layer, are plotted.

The ECC size of the BD is 2 times of that of DVD. BD ECC has 32 bytes parity, which is also 2 times of that of DVD. Within this large BD ECC-area, data is de-interleaved 2 times. Thus the defects are converted to small random errors by the de-interleaving process. Due to the large parities, randomized defects data are corrected. Fig. 6-3 shows the ECC ability of BD in the comparison of DVD ECC ability in case of 90 bytes-length burst-errors. As seen from the figure you can see the very strong defects correction capability of BD ECC. With this strong ECC, BD realizes the electronic defocus effect as shown in Fig. 6-1.

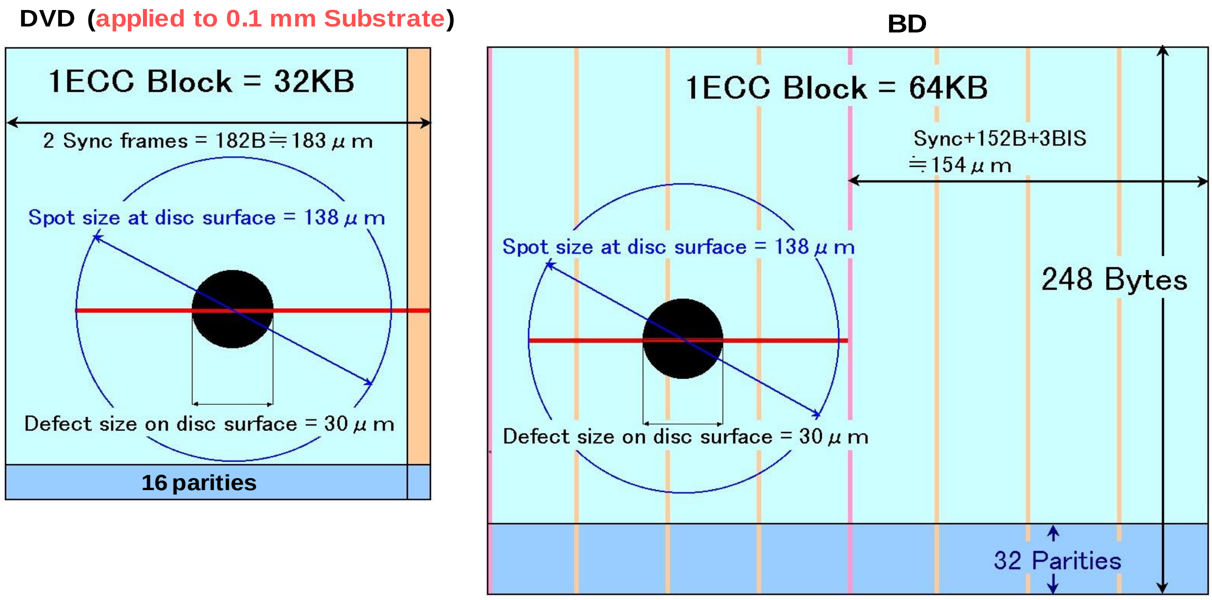


Fig. 6-2 Comparison of BD ECC Block and DVD ECC Block, which is the case applied to 0.1 mm Cover Layer system

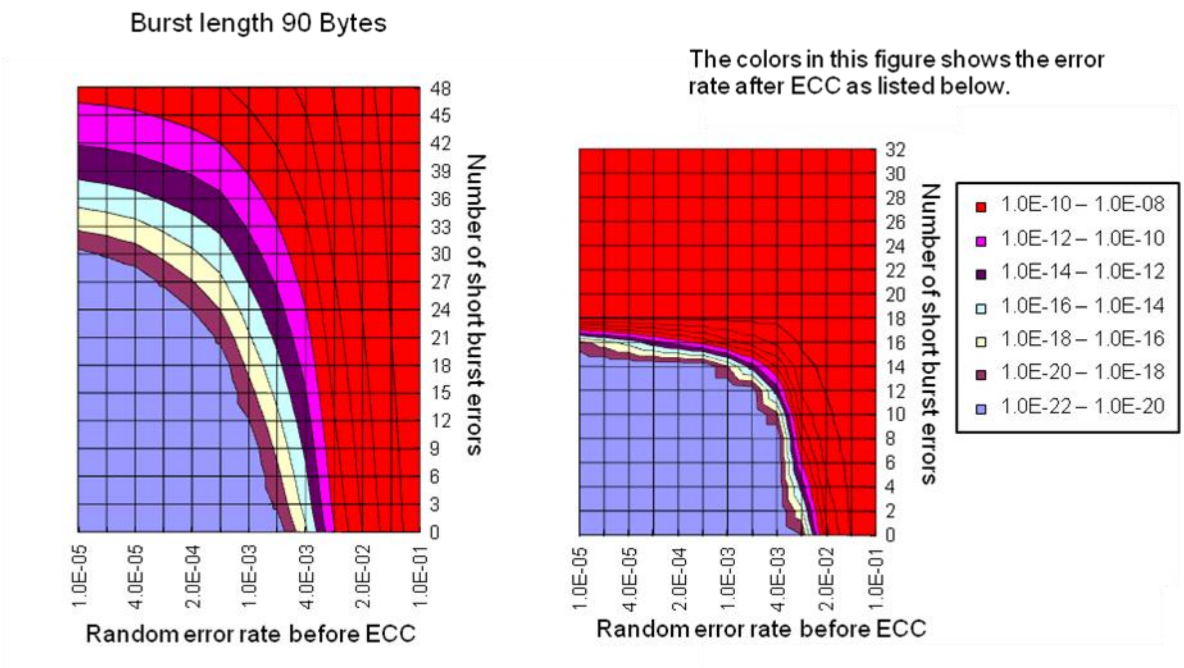


Fig. 6-3 ECC ability of BD and DVD in case of 90 bytes length burst error (Full erasure correction)

6.2 Servo stability

As explained in section 6.1, the beam spot size on the surface of the 0.1 mm Cover Layer is smaller than that of DVD. The diameter of the BD optical beam spot on the surface of the Cover Layer is 138 µm. The diameter of the DVD optical spot on the surface is 520 µm. Thus the surface spot-size of BD is roughly 1/4 of that of DVD. This smaller beam spot naturally causes a concern that the effect of fingerprints on the servo signal could be larger than that of DVD. On the other hand the Linear Velocity of a BD player is higher than that of DVD. The Linear Velocity of DVD player is 3.49 m/sec. In BD-Movie applications a BD player rotates discs 1.5 times the Reference Linear Velocity of the BD-ROM measuring condition – 7.38 m/sec or 2.11 times that of DVD player. Servo stability depends on the error-signal amplitude and the duration time during which the error signal appears. Thus there are both benefits and challenges in a BD player related to the servo system.

In order to verify servo stability, artificial fingerprints were investigated for test repeatability. There are many kinds of fingerprints and their size and pattern depends on each individual. We checked a large number of fingerprints and observed the focus-error signal, the tracking-error signal, HF signal and some calculated signals using the former 3 signals. We found that a repeated stripe pattern using UV resin showed signals very close that of the real fingerprints.

Fig. 6-4 shows the photo picture of the artificial fingerprints for the servo-stability test. In the figure, we defined the ratio of the pattern width to the repetition pitch as the duty. In case of a small duty the artificial fingerprints are like a weak fingerprint, or in other words, a “soft touch” fingerprint. In the case of a large duty the artificial fingerprint is like a heavy real fingerprint, or in other words, one applied with strong pressure. After printing these artificial fingerprints on the surface of DVD-ROM discs and BD-ROM discs, we compared the servo stability of the players.

Fig. 6-5 shows examples of the servo signals observed when these discs were used in a DVD player and in a BD player. Fig. 6-6 shows the results of the servo-stability test. Fig. 6-6 shows that the servo stability of BD players is very similar to that of DVD players. Actually, with the fingerprints, playback robustness data on the first commercial BD recorder were in general a little bit better than on most DVD recorders. We expect further improvement on BD when the player designs become more mature. Unlike write once or Rewritable discs, ROM discs have the data already recorded in the Pits pattern and so recording is not necessary.

Considering the existence of super-heavy fingerprints, we had to enable to wipe off fingerprints from the surface of a disc.

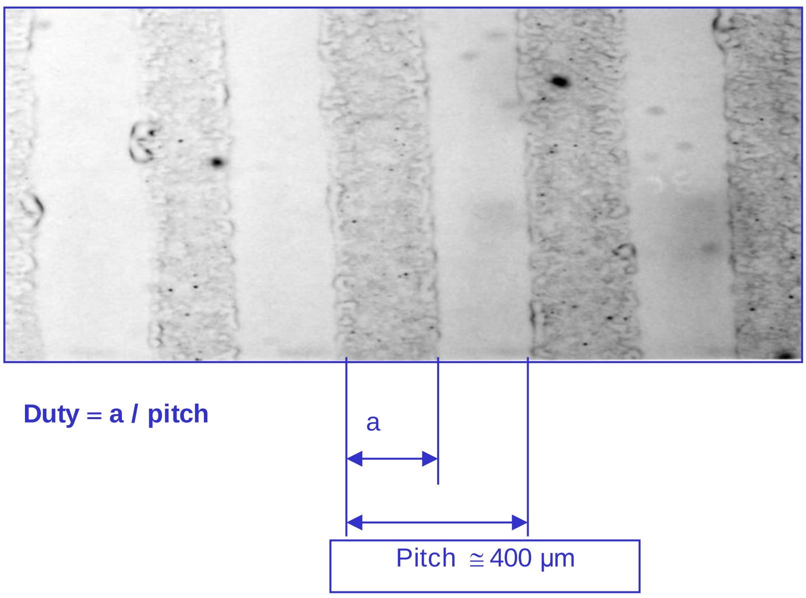


Fig. 6-4 Artificial finger prints for Servo stability test

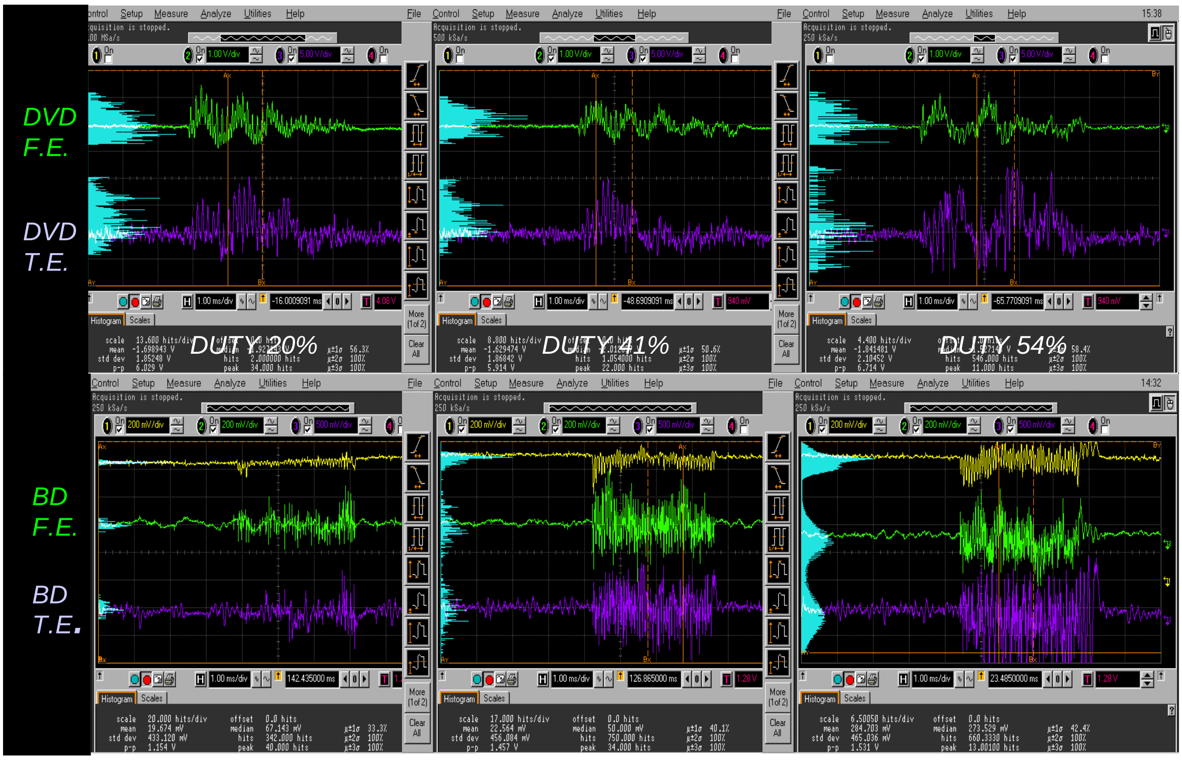


Fig. 6-5 Example of servo-error signals of DVD player and BD player

***** F.E: Focus Error T.E: Tracking Error Sum: Focus sum signal. ******

Servo-stability test result

		In DVD case		In BD case	
		Focusing	Tracking	Focusing	Tracking
Weak fingerprint	**Artificial fingerprint / Duty 20%**	**OK**	**OK**	**OK**	**OK**
Strong fingerprint	**Artificial fingerprint / Duty 41%**	**OK**	**OK**	**OK**	**OK**
Super-heavy fingerprint	**Artificial fingerprint / Duty 54%**	**OK**	**OK or NG***	**OK**	**OK or NG***

∗ Depends on player

Fig. 6-6 Results of servo stability test

6.3 Taber abrasion test

In order to wipe off fingerprints from the surface of a disc, the surface of the Cover Layer of a BD-ROM disc must be hard enough to avoid damage by a wiping action. We investigated test methods for scratch resistance. To specify hardness, we selected the Taber abrasion test. It uses a kind of abrasive roll. Two abrasive rolls are pressed on the surface of a disc with certain pressure and the disc is rotated. We investigated the relationship of jitter to the error rate and decided on the jitter value as the criterion for this test. Fig. 6-7 shows a picture of the Taber abrasion test equipment and the error rate without and with hard coat.

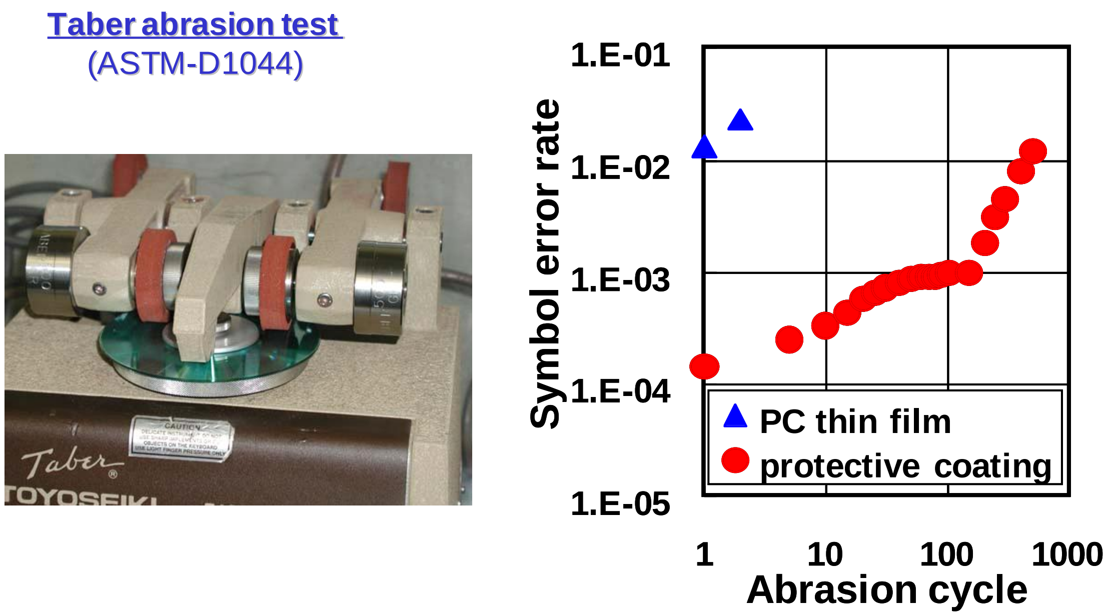


Fig. 6-7 Taber abrasion test

7. Reflectivity

Since a basic concept in the creation of the family of BD specifications was to maintain compatibility, it was determined that the BD-ROM reflectivity should be close to that of the existing BD-RE format. Technically this is possible, but disc costs have to be taken into consideration as well. For CD and DVD, Al-based Reflective Layers had been used, and no better material was found to replace this for BD-ROM. Two types reflectivity of 35 % to 70 % /12 % to 28 % are specified for the Recorded Layer of a Single-Layer (SL) BD-ROM disc, one type of 12 % to 28 % for each layer of a Dual-Layer (DL) disc and one type of 6 % to 14 % for each layer of a Triple-Layer (TL) disc, which are higher than the comparable specifications for BD-RE. (Refer to clause 2.6: Hybrid disc).

8. In-Pit and On-Pit

In general two different Pit shapes are possible as shown in Fig. 8-1. The concave Pit seen from the optical beam is defined as In-Pit and the other case (convex Pit) as On-Pit. Usually Pits that are replicated on the Substrate are In-Pits. Therefore this is the easiest way to produce BD-ROM Single-Layer discs. For Layer L1 of Dual-Layer discs the situation is different (see also Fig. 2-2 and Fig. 3-1). One method to make the Pits in Layer L1 is to replicate Pits to the Spacer Layer, which results in In-Pits. A second method is to replicate Pits to the Cover sheet, which results in On-Pits. In order to expand the possibility of disc manufacturing, both In-Pit and On-Pit geometries are allowed for BD-ROM.

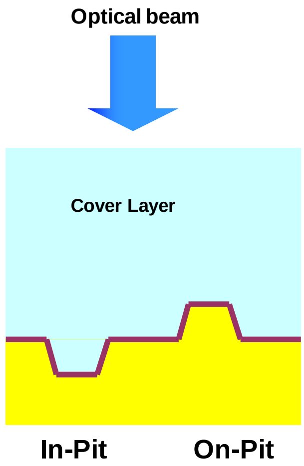


Fig. 8-1 Pit shape

9. DPD and Push-Pull tracking error

Pit depth is important for a BD-ROM disc. In order to pursue the best jitter, DVD-ROM used λ/4 for Pit depth. At λ/4 the Push-Pull signal-level is almost zero and so a DPD signal was used for the tracking signal. In the BD-ROM case the jitter is also best around a Pit depth of λ/4. Unlike DVD-ROM, the signal obtained from BD-ROM discs could not be analyzed using scalar diffraction simulation due to the high NA and shorter wavelength. Even at a Pit depth of λ/4 we can obtain a Push-Pull signal. Beyond that, we can realize good jitter and enough Push-Pull signal both below and above a Pit depth of λ/4. Thus it is not necessary to define Pit depth, which is usually defined as Pit phase.

10. Modulation

The modulation technique of the main channel recorded along a track is called 17PP ((1, 7) RLL Parity-Preserve, Prohibit Repeated Minimum-Transition Run-length code). This is a so-called d = 1 code. As the examination results show for Rewritable discs, the d = 1 code was employed for BD because of the wider detection-window as compared with the d = 2 code used for CD and DVD (see Fig. 10-1). Further, a low Channel-clock can be used when recording at high speed. This data was obtained from a past experiment using a wavelength of 650 nm. Although the horizontal axis must be transformed to the density of Blu-ray Disc™, this result was obtained when recorded and played back on a Phase-change film. The use of d = 1 means that a non-linear Equalizer and PRML detection represented by a Limit Equalizer act more effectively. This type of signal processing is more important in Blu-ray Disc™ compared with CD and DVD. Although the mastering and embossing BD-ROM Pits seemed difficult at first because the minimum Pit is shorter than that of d = 2, those processes were eventually successful thanks to the progress of mastering technology. The Parity preserve means that the DC balance of signals after modulation can be evaluated without looking at the 0-1 series, which is effective in reducing the hardware load. Prohibit RMTR(Repeated Minimum-Transition Run-length) means that the number of consecutive minimum run-lengths is limited to 6 by using a substitution rule that prevents the appearance of a long sequence of the minimum run-lengths.

Reference: “Optical Disc System for Digital Video Recording”, T. Narahara et.al., Jpn. J. Appl. Phys. 39 (2000) pp. 912-919.

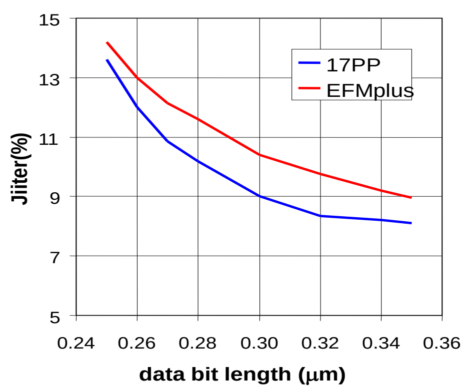


Fig. 10-1 Density comparison in two modulation codes

11. Data structure

As mentioned previously, in the case of CD and DVD, ROM discs were specified first. The data of a ROM disc are continuously recorded in those formats. When data is appended to the previously recorded data using the same data format as that of ROM for Rewritable or Write once CD or DVD discs, Zero Linking is the goal (Zero Linking means linking data without any gap or overlap). The Data-Block Unit recorded on BD-RE is a LDC (Long-Distance Code) Block of 64 Kbytes. Between the adjacent two Recording Unit Blocks, a two Sync-Frame length (Run-in + Run-out) Area is prepared, in order to handle the possible variation in Linear Velocity. We created the BD-RE specification first and so we had the flexibility to adjust the BD-ROM specification to make it similar to BD-RE specifications. For BD-RE, a wobbled groove is employed. We can use that wobble signal when we pull in the read clock during a link. But in the ROM case we do not have a wobble signal. For ROM we prepared 2 Linking Frames, which have the same length of (Run-in + Run-out) of BD-RE. We aligned the Sync Frame in the Linking Frames of a ROM disc using the same interval of the Sync Frames in the Data Area so that we can continue clocking while reading ROM discs. The Sync Frame in the Linking Frame has a unique pattern so that we can recognize the Linking-Frame Area. Fig. 11-1 and Fig. 11-2 shows the linking part of BD-RE and BD-ROM.

Physical Cluster 498 frame	Run-out 0.57 frame	Run-in 1.43 frame	Physical Cluster 498 frame

Fig. 11-1 Continuously recorded Linking part of BD-RE

Physical Cluster 498 frame	Link Frame1 1 frame	Link Frame2 1 frame	Physical Cluster 498 frame

Fig. 11-2 Linking part of BD-ROM

12. HF signal quality evaluation method

In this chapter, HF signal quality evaluation methods of BD-ROM disc are explained. The signal quality of the disc with 25GB/layer is evaluated by a jitter measurement using the Limit-Equalizer. The signal quality of the disc with 33.4GB/layer is evaluated by an i-MLSE measurement.

12.1 Jitter measurement using Limit-Equalizer

Generally, a playback signal reading system uses a Linear Equalizer to improve the Signal–to-Noise Ratio (SNR) around minimum-length Pits and to suppress Inter-Symbol Interference. Disc noise exists mainly in a low-frequency region as shown in Fig. 12-1. When high frequency around minimum-length Pits is selectively boosted using the Linear Equalizer, the minimum-Pit-length signal-level can be markedly enhanced with only a small increase in the total amount of noise. That is, it is possible to improve the SNR by using a Linear Equalizer that boosts high frequencies. However, since an excessive boosting of high frequencies causes an increase in Inter-Symbol Interference, the Conventional Linear Equalizer has a limit to SNR improvement. A Limit Equalizer is capable of boosting high frequencies without increasing Inter-Symbol Interference. Fig. 12-2 shows the configuration of the Limit Equalizer system used in 17PP modulation. In this system, a Pre-Equalizer first minimizes Inter-Symbol Interference.

A Conventional Linear Equalizer is used as the Pre-Equalizer. The Limit Equalizer is located next to the Pre-Equalizer. The Limit Equalizer has almost the same construction as a Finite-Impulse-Response (FIR) Linear Equalizer, except that the Limiter restricts the amplitude of part of playback signal. The FIR filter acts as a high-frequency-boosting Equalizer, and its gain is determined by coefficient “k.” The gain of the FIR filter increases with the value of k.

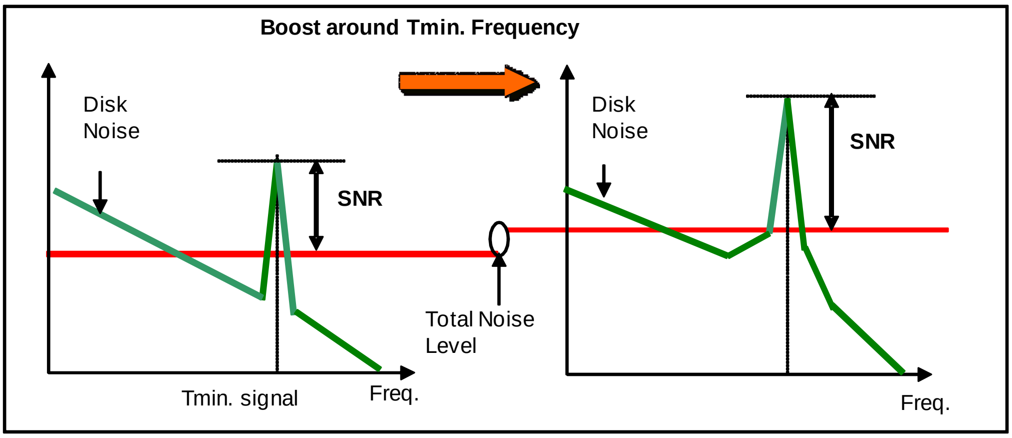


Fig. 12-1 Improving SNR by boosting high-frequency signal

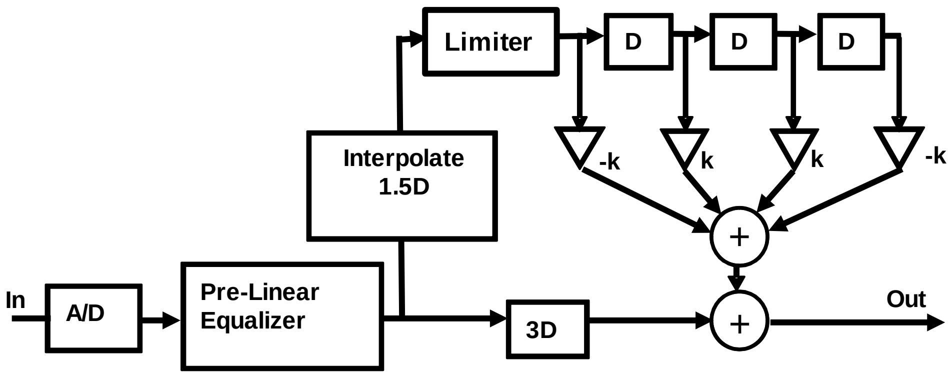


Fig. 12-2 Configuration of Limit Equalizer

Sample values of the playback signal are indicated at the small-circle points in Fig. 12-3. To understand the operation of the Limit Equalizer, we pay attention to the zero-cross point and the sample values at points close to the zero-cross point. The operation of the Equalizer without a Limiter is as follows.

Referring to the left-side chart of Fig. 12-3, if the playback signal waveform is symmetrical as indicated by the solid line, the data summed up by the Equalizer becomes 0 as expressed in Equation (1), and the zero-cross point does not move.

(-k)x(a) + (k)x(a) + (k)x(-a) + (-k)x(-a) = 0 --- (1)

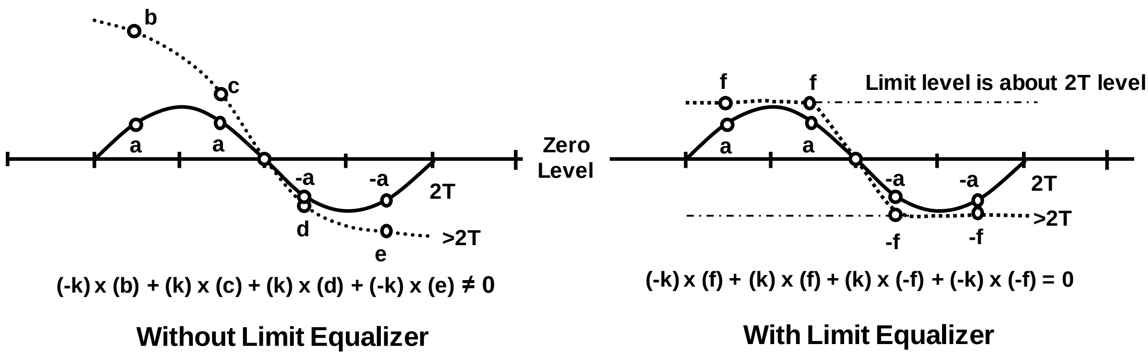


Fig. 12-3 Behavior of Linear Equalizer and Limit-Equalizer

However, if the playback signal waveform is asymmetrical as shown in the dotted line, the data summed up by the Equalizer does not become 0 as indicated by Equation (2), resulting in the Inter-Symbol Interference.

(-k)x(b) + (k)x(c) + (k)x(d) + (-k)x(e) ≠ 0 --- (2)

However, if a Limiter is used to restrict the signal amplitude to around the peak amplitude level of the shortest wavelength signal, the waveform becomes symmetrical as shown by the dotted line in the right-side chart of Fig. 12-3. In that case, the data summed up by the Equalizer is constantly 0, as expressed in Equation (3).

(-k)x(f) + (k)x(f) + (k)x(-f) + (-k)x(-f) = 0 --- (3)

The Limiter does not act on a signal with minimum-length Mark, and the Equalizer amplifies the signal amplitude. For a low-frequency signal with high amplitude, the Limiter restricts the amplitude around the center tap, which is to be added to the sum. The filter gain is effectively decreased. Thus, the Limit Equalizer can boost high frequencies without increasing Inter-Symbol Interference, and SNR is improved.

Since the Blu-ray Disc™ format adopts high-density recording and 17PP modulation, the minimum-Mark length is shorter than for a conventional optical-disc, and its SNR is lower. The Viterbi decoding in the drive can compensate for the lower SNR to achieve good playback performance. However, since Viterbi decoding output is the result after 1/0 determination and is poor in sensitivity, it is not suitable for use in evaluating optical discs in general. The jitter of signals processed by a Linear Equalizer is dominated by the component attributed to the noise of disc itself rather than the component attributed to the quality of Recording Marks, making it difficult to determine whether or not the recording state is optimal. In this regard, a Linear Equalizer is not suitable for use in disc evaluation.

The Blu-ray Disc™ system employs a Limit Equalizer to improve the SNR and to measure jitter for disc evaluation. With the Limit Equalizer, it is possible to determine the quality of Recorded Marks with high sensitivity. Fig. 12-4 shows the relation of jitter to the error rate.

Though the Limit Equalizer has a non linear operation block inside, the relationship of input to output is linear and suitable as measurement system.

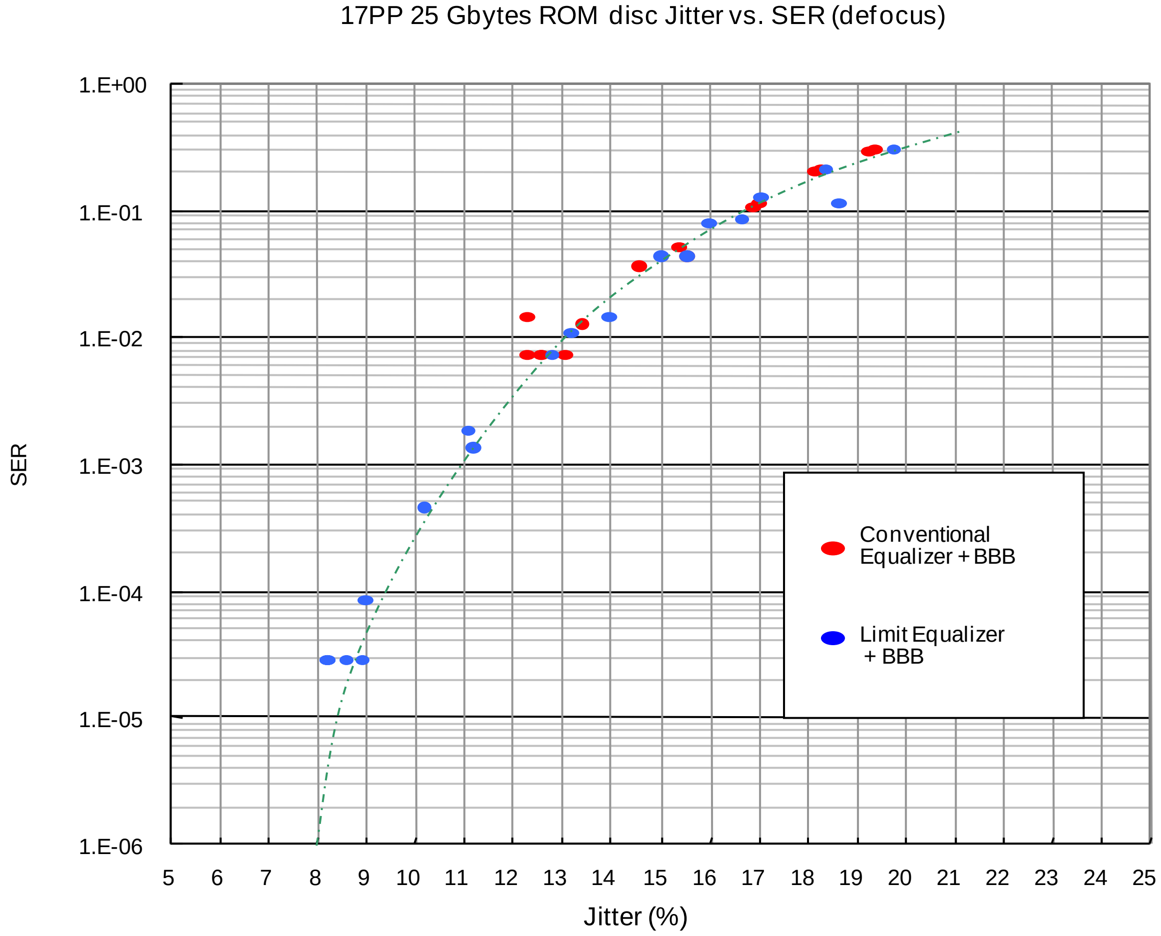
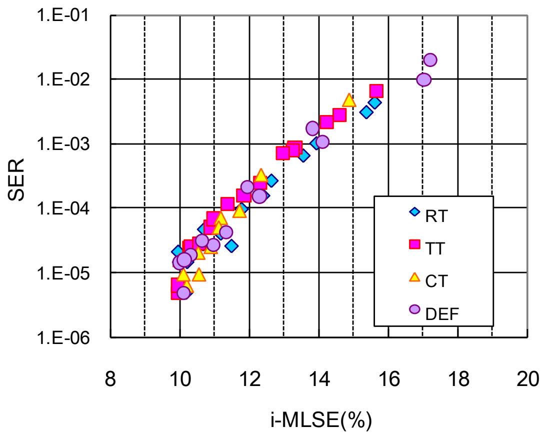


Fig. 12-4 Relation of error rate and Jitter of Conventional Equalizer and Limit-Equalizer

12.2 i-MLSE measurement

Introduction

In 66GB disc and 100GB disc of Blu-ray Disc™ Read-Only format (Ultra HD Blu-ray™) the capacity per layer is raised up to 33.4GB only by increasing the linear density. As a result, the Inter-Symbol-Interference (ISI) of the readout signal becomes much stronger compared to the prior format that allows just 25GB per layer. Therefore the readout signal-processing needs to be improved. Also, the prior signal quality evaluation method using the Limit-Equalizer technology has turned out to be no longer applicable. Integrated-Maximum Likelihood Sequence Error Estimation (i-MLSE), which was developed as a signal quality evaluation method for BDXL™, retains the stability and the precision in such a severe ISI condition. The evaluation method of i-MLSE stands on the detection principle of the Viterbi-Algorithm (VA) in the Partial Response Maximum Likelihood (PRML) readout signal processing. Additionally, some contrivances can be incorporated to achieve the better correlation with the Symbol-Error-Rate (SER). For example, the tendency of error occurrences with the PR(1,2,2,2,1)ML readout in the Ultra HD Blu-ray™ is considered. Another feature of i-MLSE is that the mathematical expression is the same as that of Jitter, which is the prior signal quality evaluation method. Consequently, the behavior of i-MLSE is very similar to that of the Jitter. This helps people who evaluate the Ultra HD Blu-ray™ discs or systems for the first time to comprehend the meaning of measured values obtained through i-MLSE because the Jitter has been used so long since the era of CDs and is very familiar to them.



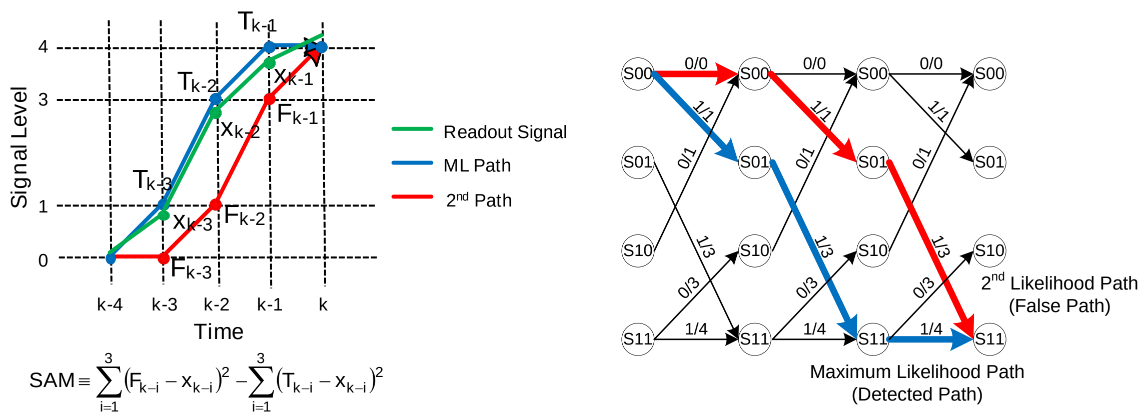
Readout Skew
RT: Radial-tilt
TT: Tangential-tilt
CT: Cover-Thickness error
DEF: Defocus

Fig. 12-5 i-MLSE and SER correlation

Fig. 12-5 shows measurement results of i-MLSE and SER for BDXL™ discs under various kinds of readout conditions. All plots including different kinds of readout conditions are approximately on the same curve. In other words, well-matched correlation performance of i-MLSE is demonstrated here.

Basic theory of i-MLSE

i-MLSE is calculated from Sequenced-Amplitude-Margin (SAM) that indicates the reliability of VA. SAM is an instantaneous value that is defined as the path-metric differences between the Maximum-Likelihood-path (ML-path: decoded result in VA) and the Second-Likelihood-path (2nd-path) as shown in the left side figure of Fig. 12-6. In VA the path that has the smallest path-metric survives as the more-likelihood path at every state to which several branches are inflowing, as shown in the right side trellis diagram of Fig. 12-6. Therefore, the detection reliability of VA can be quantified by how smaller the path-metric of the ML-path compared to the rivalry paths' path-metric, in other words, how large the SAM value is.



$$SAM \equiv \sum_{i=1}^{3}(F_{k-i}-x_{k-i})^2-\sum_{i=1}^{3}(T_{k-i}-x_{k-i})^2$$

Fig. 12-6 Calculation of SAM value

In Fig. 12-6, left figure shows how to calculate the SAM value and right figure shows the trellis diagram of VA. Although PR(1,2,2,2,1)ML with d=1 run-length limited (i.e., ten states) is employed in the Ultra HD Blu-ray™ specification, simpler PR(1,2,1)ML with d=1 run-length limited (i.e., four states) is assumed in these figures for ease of understanding of the concept of SAM.

Generally, readout waveforms are distributed around ideal waveforms (i.e., ML-paths). In these cases, the distribution of SAM values is revealed to be approximately a normal distribution which means SAM value is almost equal to the square Euclidean distance between ML-path and 2nd-path. By fitting the SAM distribution to the normal distribution we can calculate the error rate from the probability of appearance of the region in which SAM<0. If the SAM distribution can be approximated as a single normal distribution from the viewpoint of prediction of error occurrences, the evaluated value of i-MLSE can be defined in completely the same manner as in the prior Jitter. But actually, there are several error-dominant patterns which have different Euclidean distances and different variances (i.e. plural different normal distributions). Therefore, to quantify the signal quality by a single value, it is required to evaluate contributions of the estimated errors from plural distributions with different variance and different mean value. In i-MLSE three groups of error-patterns are evaluated as error-dominant patterns as shown in the Table 12-1.

Group Name	Group 14	Group12A	Group 12B
Error mode	One bit shift	Single 2T shift	Consecutive 2T shift
Euclidian distance (d_k)	$\sqrt{14}$	$\sqrt{12}$	$\sqrt{12}$
Truth and Error Bit pattern (example)	T:000001111 E:000011111	T:00000110000 E:00001100000	T:0000011001111 E:0000110011111

Table 12-1 Evaluating error-pattern of i-MLSE

<u>Calculation of i-MLSE</u>

For simplifying the numerical expression, we define normalized-SAM (ξ_k) for SAM of the k-th error-pattern as follows;

$$\xi_k \equiv \frac{SAM_k - d_k^2}{2d_k^2}$$

where d_k^2 represents the square Euclidean distance of the k-th error-pattern. i-MLSE is calculated in the following three steps. In the first place, for the purpose of quantifying the quality of the signal, mean value (η_k) of the minus side of ξ_k distribution with respect to its mean value (μ_k) is calculated (Fig. 12-7). Under the assumption of the normal distribution for ξ_k, the estimated bER of the k-th error-pattern ($ebER_k$) and η_k has the relationship as follows;

$$ebER_k = \frac{\rho_k W_k}{2} \operatorname{erfc}\left(\frac{1+2\eta_k}{2\sqrt{\pi}(\mu_k - \eta_k)}\right)$$

where ρ_k denotes the frequency of the k-th error-pattern, W_k denotes the Hamming distance of the k-th error-pattern and erfc(x) denotes the complimentary error function. Then, the total estimated bER ($ebER_{total}$) is obtained by adding each $ebER_k$ for all error-patterns. This manner is very straightforward, but the integration among the different error-patterns can be performed most accurately. Finally, i-MLSE ($\sigma_{i\text{-}MLSE}$) is obtained by converting $ebER_{total}$ to the equivalent normalized standard deviation (i.e. the jitter value) by following equation:

$$\sigma_{i\text{-}MLSE} \equiv \left\{2\sqrt{2}\operatorname{erfc}^{-1}\left(\frac{2\cdot ebER_{total}}{\rho_{total}}\right)\right\}^{-1} \Leftrightarrow ebER_{total} = \frac{\rho_{total}}{2}\operatorname{erfc}\left(\frac{1}{2\sqrt{2}\sigma_{i\text{-}MLSE}}\right)$$

where $\operatorname{erfc}^{-1}(x)$ denotes the operation of the invert function of the complimentary error function.

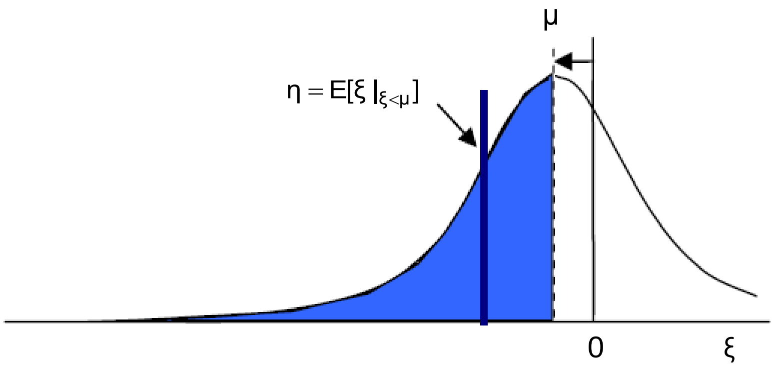


Fig. 12-7 Signal quality estimation by one-sided mean value of normalized SAM distribution

13. Disc manufacturing process

Currently a 3 to 3.5 sec. cycle time for BD-ROM disc-manufacturing has been confirmed; as well as cost estimation compared to red DVD (1.1 times up for SL and 1.5 times up for DL). In this chapter the key technologies for disc manufacturing are explained.

13.1 Mastering

Three kinds of mastering systems are available now. Those three methods were used to make the test discs for the BD-ROM specification working group.

1) The PTM (Phase-Transition Metal) mastering-system uses a blue laser diode as light source and it is a promising method to realize a compact and low-cost mastering-system.
2) The deep-UV liquid-immersion mastering system uses water between the high-NA lens and the photo-resist. It resembles a conventional mastering-system and is already available from a European company.
3) The electron-beam recorder is more expensive but it gives the highest resolution.

13.1.1 PTM (Phase-Transition Metal) mastering

PTM Recorder

The basic concept of this technique is to use a special inorganic material that changes phase from as-deposited amorphous to crystal when exposed to laser light. The exposed or crystallized region becomes soluble in conventional developing-fluid. The material is thus a kind of inorganic photo-resist.

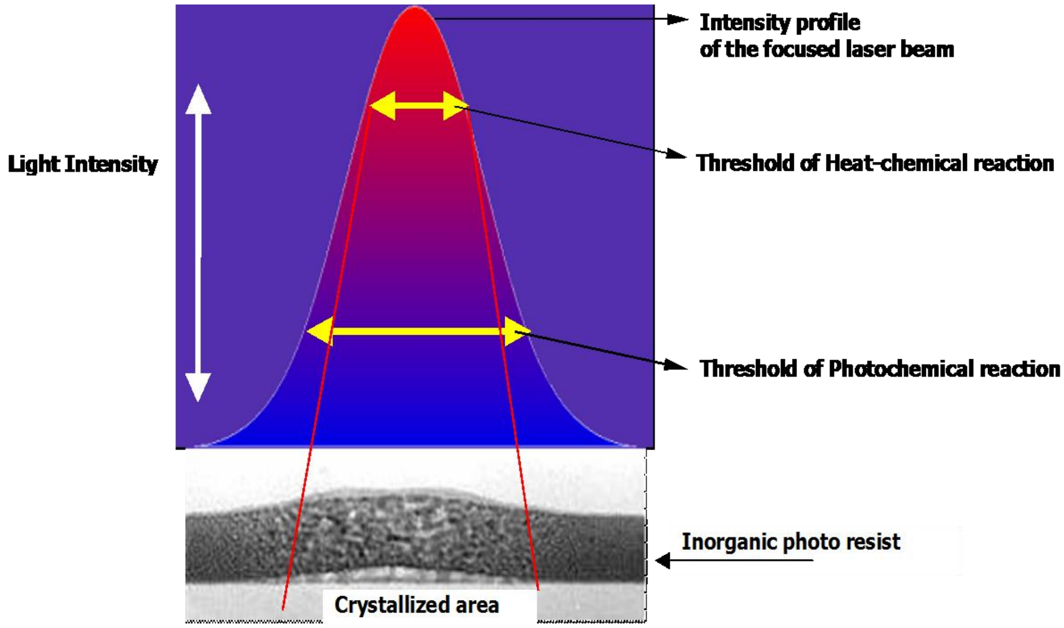


Fig. 13-1 PTM recording mechanism

Fig. 13-1 explains the mechanism of the cutting process. This inorganic material has sensitivity at a wavelength of 405 nm, which is close to that of the conventional gas-laser used for cutting CD and DVD signals. A 0.95 Numerical-Aperture lens is employed in this recorder, which is also used in conventional mastering-systems. The phase change of this inorganic resist is induced through a heat-chemical reaction, not through a photochemical one. So only the material area that is heated above the threshold temperature reacts to the laser and gets crystallized. This is the reason why the Recorded Mark is smaller than the laser spot. A silicon wafer is used for the Substrate for sputtering this inorganic material mainly because of its moderate heat conductivity, which is larger than the conventional glass-master but not by much. The optical pick-up and the drive electronics for the laser of the PTM system are quite similar to those used in the Blu-ray™ recorder. A variety of multi-pulse write-strategies to improve signal quality can be applied, if necessary. A change in reflectivity accompanies the Phase-change process. So, the cutting performance during cutting can be monitored by just observing the changes in reflectivity. Taking advantage of this, the optimum cutting-condition can easily and quickly be found with the PTM system. It is not needed to go through the whole mastering-process to make a stamper in order to get feedback for a next trial-cutting. Real time optimization of the cutting parameters is one of the key features of the PTM system. Because its optical pick-up is similar to one for a conventional Blu-ray™ recorder, the PTM system is small, light, reliable and stable with low energy- consumption. Plus, unlike the conventional cutters with gas lasers, no cooling water is needed at all.

PTM process

As we use a silicon wafer and an inorganic photo-resist for PTM, we can make a stamper directly after developing the silicon wafer. In addition, because the inorganic photo-resist is hard and robust, we can multiply the original stamper as many as 10 times, simply by replicating, without any deterioration in signal quality. By use of relatively cheap and abundant silicon wafers for the master substrates, we succeeded in eliminating many of conventional processes like glass polishing, drop-out checking, photo-resist coating, metal plating, metal mastering and mother fabrication. This simplification of the process provides us with numerous benefits of comprehensive cost-reduction. These include, for example, cutting down the consumption of chemicals, minimizing the clean room footprint, elimination of inspection processes and reduction of utility and maintenance costs. Lastly, with fewer process steps made possible by PTM, reproducibility of the products will be improved dramatically. Thus PTM is an ideal mastering system both for mass production and for R&D (Fig. 13-2).

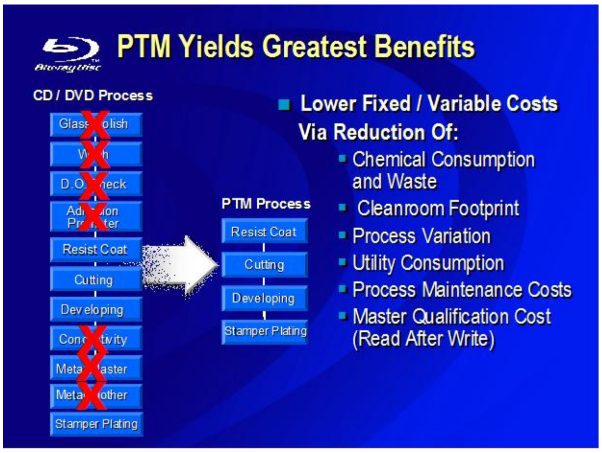
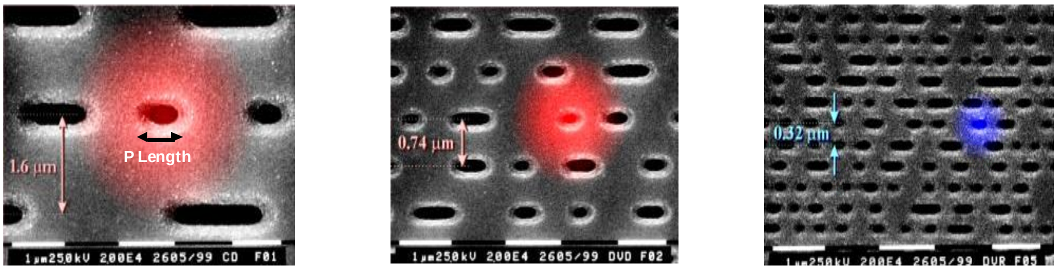


Fig. 13-2 Great benefits for PTM process

SEM observation of the Ni stamper mastered with PTM reveals the characteristic shape of the Pits (Fig. 13-3). A Push-Pull signal is used for radial tracking in the Blu-ray™ RE format. To make BD-ROM and RE compatible, it is preferable to define a Push-Pull signal in the BD-ROM format also. The Pit shape materialized by the PTM process is almost ideal in that excellent Push-Pull signals and RF signals can be reproduced from those Pits at constant Pit depth. A BD-ROM disc was made for signal evaluation, forming a 0.1 mm-thick Cover Layer in line with the basic concept of the Blu-ray™ format. Judging from the eye patterns and the jitter values, we can confirm the ROM signals mastered by PTM are compatible with the specifications for BD-RE. The signal properties also proved homogeneous over all disc radii (Fig. 13-4). Also, in the Dual Layer structure, the signals mastered by PTM reveal equivalent properties (Fig. 13-5). Furthermore, the discs made from the stamper of 10th replication show almost the same jitter values as the one made from the first stamper.

CD 0.7 GB	DVD 4.7 GB	Blu-ray Disc™ 25 GB



Track Pitch : 1.6 µm	Track Pitch : 0.74 µm	Track Pitch : 0.32 µm
Minimum-Pit Length: 0.8 µm	Minimum-Pit Length: 0.4 µm	
Storage Density : 0.41 Gb/in²	Storage Density : 2.77 Gb/in²	Storage Density : 14.73 Gb/in²

Fig. 13-3 SEM photo of BD compared with CD and DVD

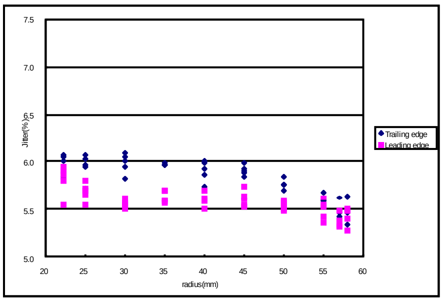
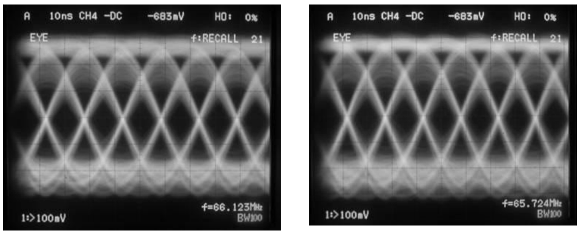


Fig. 13-4 Jitter distribution



Layer L0 — Jitter 5.6 %

Layer L1 — Jitter 5.8 %

(Limit Equalizer)

Fig. 13-5 Jitter of Dual Layer

13.1.2 Deep-UV Liquid-Immersion mastering

Introduction

One of the greatest advantages of optical discs such as CD and DVD is the ease and low costs of ROM reproduction. Mastering is the key step in making the stamper from which ROM discs are replicated. For the Blu-ray Disc™ generation, evolutionary optical-disc mastering-equipment as yet is unable to write the 25 GB ROM required in BD-ROM because of the size of the writing spot. Liquid immersion is an elegant solution to this problem, adding to the advantages of optical-disc mastering without too large impact on existing infrastructure.

Method and Results

The small spot necessary to write the tiny pits in BD-ROM can be made using the Liquid-immersion principle, well known in microscopy. At first sight, Liquid immersion seems impractical in a mastering machine with high writing velocities and with high demands on mechanical stability. However, the solution developed eliminates these issues, as illustrated in Fig. 13-6 and Fig. 13-7.

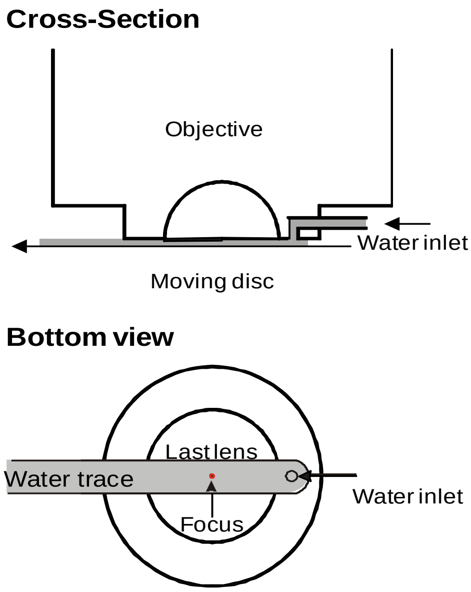


Fig. 13-6 Liquid immersion concept

A minimal amount of liquid, in total 30 ml per 25 GB disc, is injected upstream of the writing spot and removed downstream. The resulting system is very much like a normal laser beam recorder as is applied in CD and DVD mastering. Fig. 13-8 shows an AFM image of the resulting Pits and Fig. 13-9 shows the corresponding read-out signals. The jitter is better than 5 %, which is well below the limit of 6.5 %.

Concluding remarks
Liquid-immersion mastering is an optical-mastering solution capable of mastering BD-ROM without too large impact on existing mastering-infrastructure.

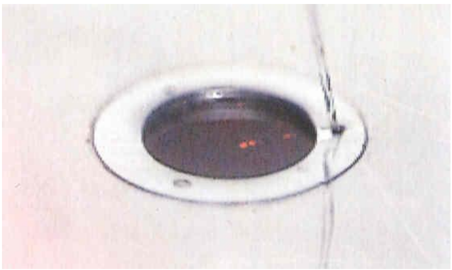


Fig. 13-7 Bottom element of Liquid-immersion objective.

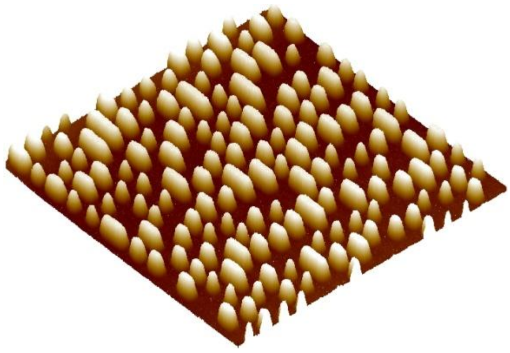


Fig. 13-8 AFM measurements of 25 GB ROM

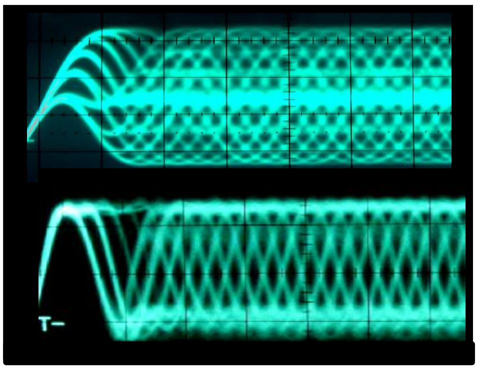


Fig. 13-9 Eye-pattern without and with Limit-Equalizer

13.1.3 Electron-beam mastering

High-resolution performance of a mastering machine is required to produce high-density optical-discs. A conventional-type Laser-Beam Recorder (LBR) can not master a high-density optical-disc because of its low-resolution performance. To improve resolution, an Electron-Beam Recorder (EBR), which has an electron-emitting source, was developed. An outline of the EBR is explained as an example. Its schematic illustration is shown in Fig. 13-10. A work chamber is supported with the vibration-control unit which works as the foundation. An electron-beam column is mounted on the center of the work chamber. The secondary-electron detector is on one side of the column. An illumination part and a detection part of a height sensor are located on opposite sides of the column.

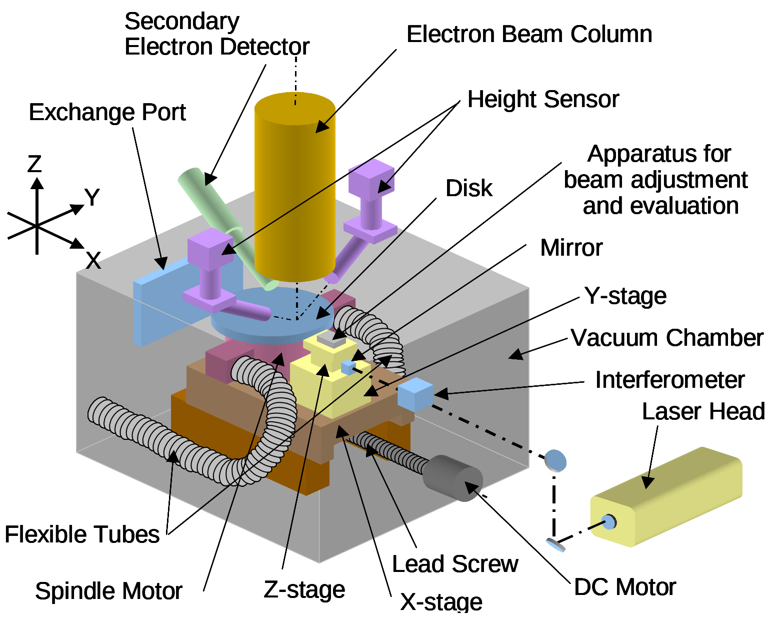
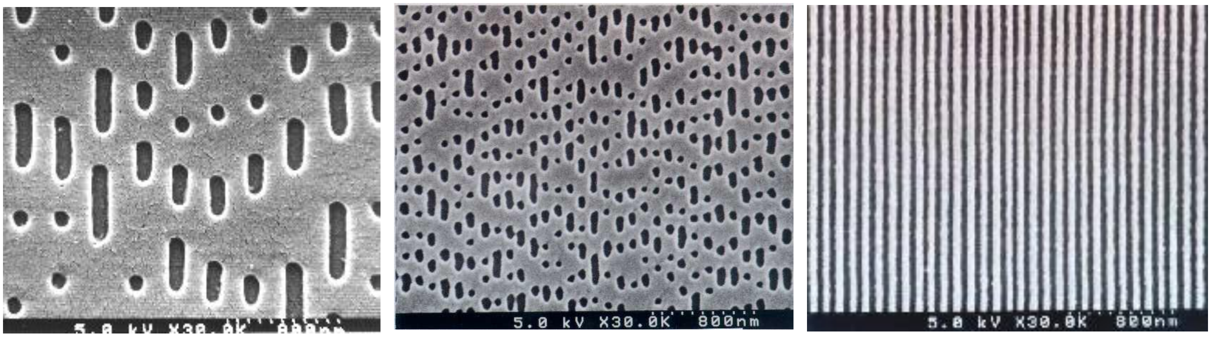


Fig. 13-10 Schematic view of EBR

A carriage stage moves in the X-direction by a dc motor and a lead screw. A vacuum-sealed air spindle-motor is mounted on the top of the stage. The emitting source is a thermal-field emitter (TFE). The electron beam emitted from the TFE is focused onto the disc surface with two lenses within the column. Using a 6 m-rad convergence semi-angle with 50 keV beam energy, a beam current and a beam diameter (Full Width at Half Maximum) are measured as 130 nA and 55 nm respectively. Beam modulation is carried out by a pair of blanking plates, arrayed in the column, with a rise time of about 10 ns. Surface vibration and the height of the disc are constantly measured during recording by the optical height-sensor. Beam focus is controlled at the disc surface by adjusting the focal distance according to the signal information from the optical height- sensor. The recording position in the track direction is controlled as follows. The stage position is determined by measuring a mirror position placed on the stage with a laser interferometer. The residual error-signal of a position-servo system is fed forward to the dc motor and also to the beam deflector in the column. Thus, the recording-track position is corrected with the beam deflection.

Fig. 13-11 shows the spiral recording-patterns made by using the EBR. Fig. 13-11 (a) shows the pit pattern of a 25 GB ROM disc. The recording parameters are a 320 nm-Track Pitch and a 149 nm minimum-Pit length. A jitter value below 5 % was achieved. Though apart from BD specifications, Fig. 13-11 (b) and (c) show the high-density recording possibility of EBR, with Pit and line patterns at a 3 m-rad convergence semi-angle. The EBR is confirmed as a promising technology for advanced high-density recording. The development of the EBR with high resolution performance is almost complete, and development and commercialization of the EBR are going ahead in consideration of future disc mass-production. For electron-beam recording, the key remaining issue is the efficiency of mass production caused by slower recording-speeds. It requires about 10 hours to record a full-size disc using a conventional-type resist. As one solution for this issue, using a chemically-amplified resist is a promising scheme to greatly improve the efficiency of mass production. Several companies reported recording experiments at over 2.5 m/s speed at a recent international conference on optical discs. The possibility of real-time recording is expected by selecting a suitable resist for optical-disc mastering and by improving the recording strategy.



(a) 25 GB ROM (b) 201 GB ROM (c) 50 nm line and space

Fig. 13-11 SEM image of EBR recording pattern

13.2 Disc-replication process

Replication process

Fig. 13-12 shows a manufacturing process for a Single-Layer disc. The injection-molded Substrate cools down while moving to the bonding unit. Then the Reflective Layer is formed on the Substrate by sputtering. The Reflective Layer is covered with UV-curable resin by spin coating. Next the outer round area of the Resin Layer is heated by IR irradiation so that its viscosity is decreased.

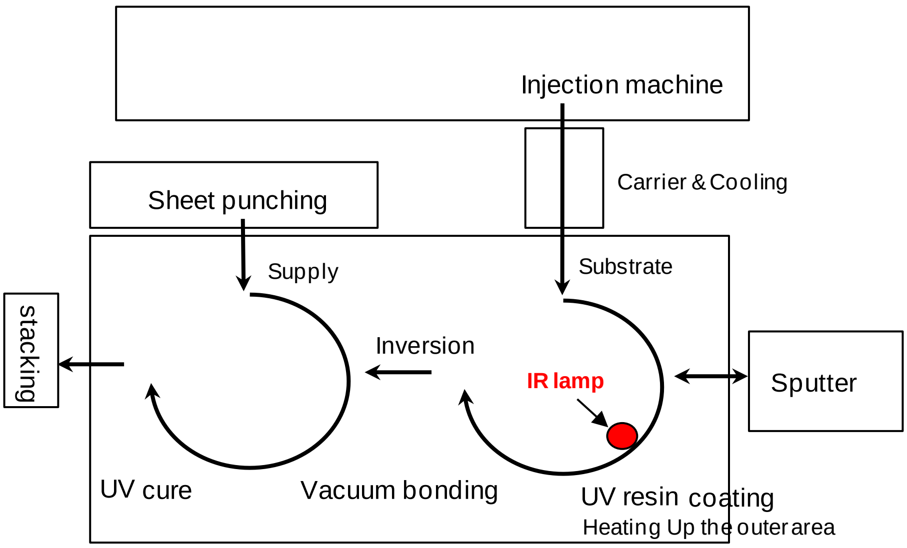


Fig. 13-12 Single-Layer process

In the meantime Cover sheets are punched out from a roll and supplied to another rotating part of this unit one after another. The Substrate with UV resin is turned over and set on the Cover sheet. Finally, the Cover sheet is glued to the Substrate by curing the resin through UV irradiation.

Fig. 13-13 shows the variation of the Cover-Layer thickness of a disc that satisfies the specification. Fig. 13-14 shows the thickness variation of 3000 discs produced by this process consecutively. Fig. 13-15 shows disc warp caused by a sudden environmental-change from 30 deg.C and 90 %RH to 23 deg.C and 50 %RH. We confirmed that the disc warp was well within the specification even under such a harsh environmental condition.

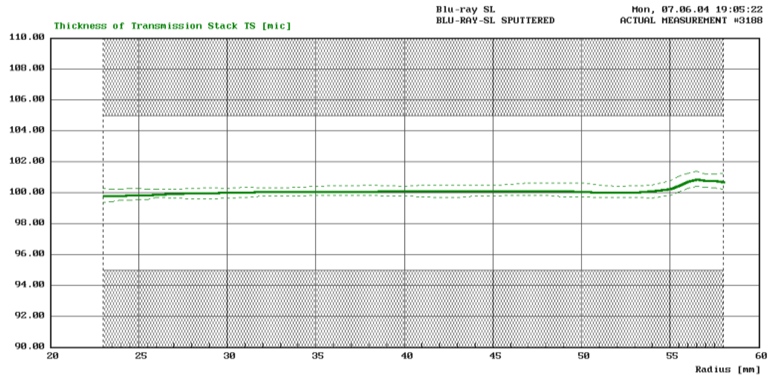


Fig. 13-13 Thickness variation

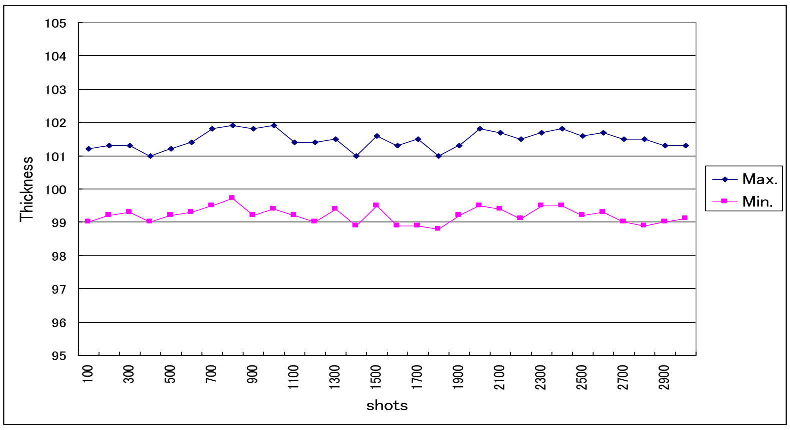
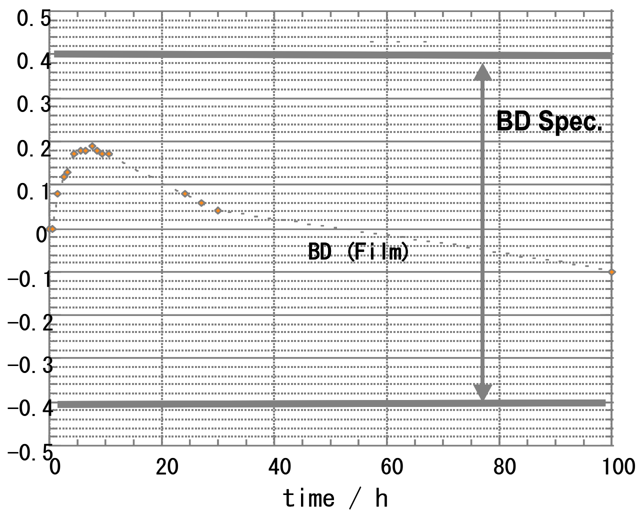


Fig. 13-14 Cover-Layer thickness variation for 3000 disc series



30℃、90%RH、3days→23℃、50%RH (r = 57mm)

Fig. 13-15 Disc warp in sudden environmental change

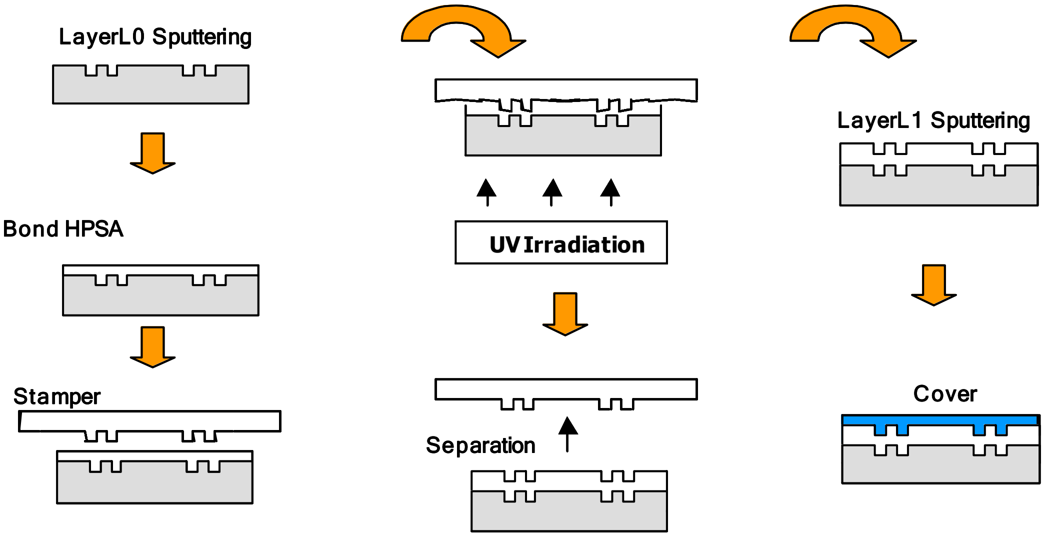


Fig. 13-16 Manufacturing process for Dual-Layer disc

Fig. 13-16 shows a manufacturing process for a Dual-Layer disc. Layer L0 is formed on the Substrate by sputtering first and the Spacer Layer, which is made of UV-curable adhesive called HPSA (Hardenable Pressure-Sensitive Adhesive), is formed on it by pressure-bonding. A stamper is set on the HPSA and pressed for replicating the signal Pits. Then UV light is applied through the Substrate from the backside. After that, the stamper is removed and the semi-reflective Layer L1 is sputtered on the HPSA. The Cover-Layer process for a Dual-Layer disc is the same as the one for the Single-Layer disc. Jitter data for Dual-Layer discs is shown in Fig. 13-5. Fig. 13-17 to Fig. 13-20 show the thickness variation of a typical Cover Layer, a typical Layer L1, a series of 1000 Layer L1s, a typical Layer L0 and a series of 1000 Layer L0s, respectively.

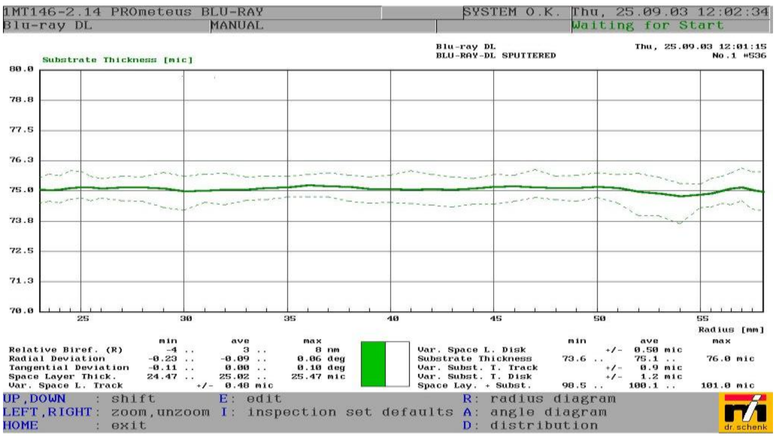


Fig. 13-17 Thickness variation of Layer L1

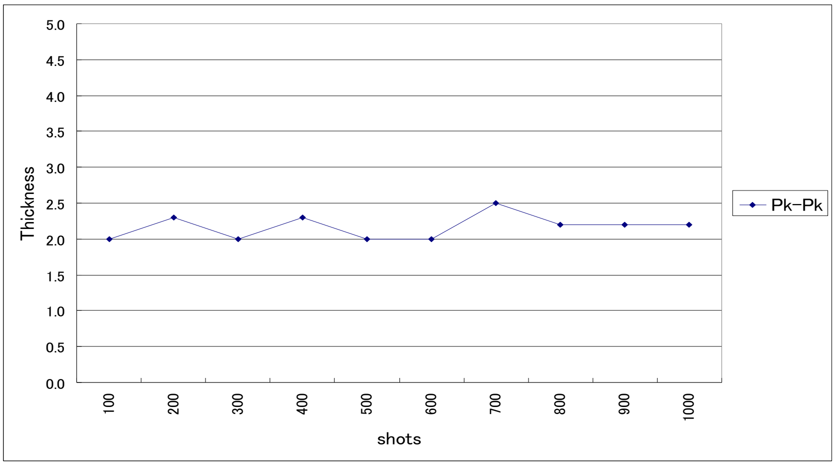


Fig. 13-18 Layer L1 thickness-variation for 1000 disc series

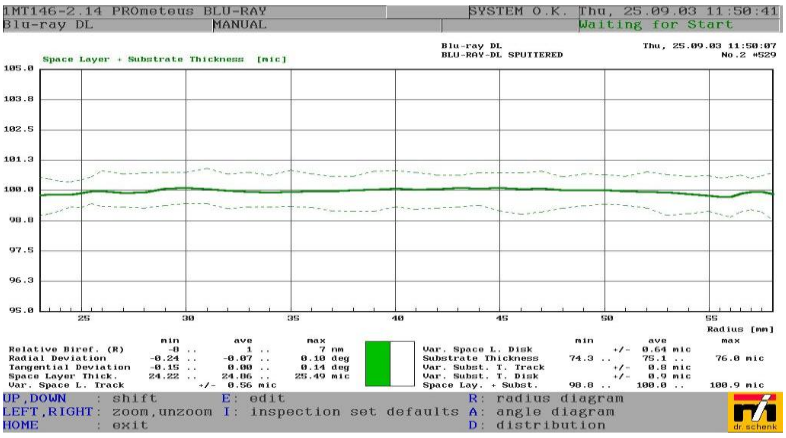


Fig. 13-19 Thickness variation of Layer L0

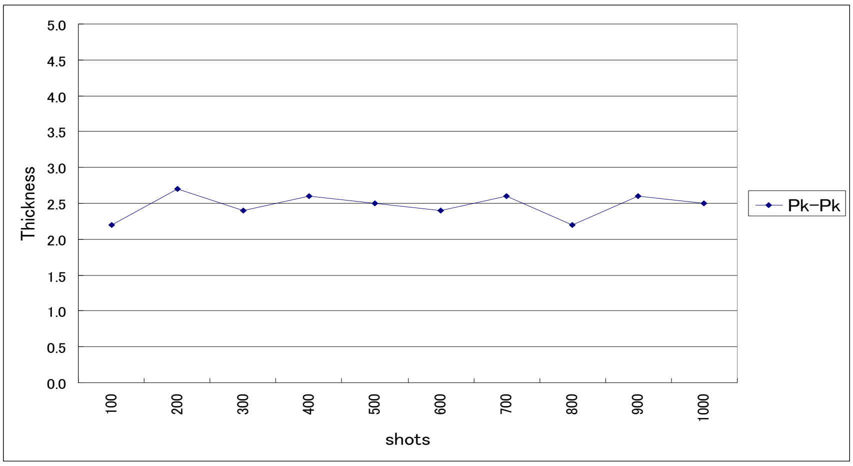


Fig. 13-20 Layer L0 thickness variation for 1000 disc series

Lastly, Fig. 13-21 compares the main parameters with a typical result.

		BD-ROM parameters	Measured result
Scanning Velocity	[m/s]	4.92	4.92
Disc imbalance	[gmm]	< 4.0	1
Disc mass	[g]	12 to 17	15.6
Spacer-Layer thickness	[µm]	20 to 30	24 to 26
Cover-Layer thickness-variation	[µm]	± 3	± 1.2
Refractive index		1.45 to 1.70	1.61
Radial tilt	[°]	≤ 1.60 pp	0.80 pp
Birefringence	[nm]	≤ 30	10
Reflectivity of SL	[%]	35 to 70	50
Reflectivity of DL	[%]	12 to 28	20
Lead-in start radius	[mm]	22.0 +0.2, -0	22
Data start radius	[mm]	24.0 +0, -0.1	24
Radial runout	[µm]	≤ 75 pp	50 pp
Radial LF residual-error(SL)	[nm]	≤ 9	7
Radial HF residual-error(SL)	[nm]	≤ 6.4 rms	4 rms
Jitter Layer L0 (Limit Equalizer)	[%]	≤ 6.5	5.8
Jitter Layer L1(Limit Equalizer)	[%]	≤ 8.5	6.5
Asymmetry		-0.10 to +0.15	+0.08
Symbol Error Rate		$< 2 \times 10^{-4}$	1×10^{-5}

Fig. 13-21 Typical measured results of BD-ROM

14. SID code

The SID (Source Identification) code is a code to be recorded at the inner part of a disc. It is made up of visible characters that identify the manufacturer of the master and the disc. There are two kinds of codes: a Mastering Code and a Mold Code.

The Mastering Code is created by using the master recorder, which means that this code is also present on the stamper.

The Mold Code is etched on the mirror block side of the mold.

When a Substrate is replicated, the Master Code will appear on the same side of the Substrate as the embossed Pits, the Mold Code will appear on the opposite side of the Substrate.

These 2 codes can be used to trace the location where the master and/or discs are made.

Fig. 14-1 shows an example of the Mold Code.

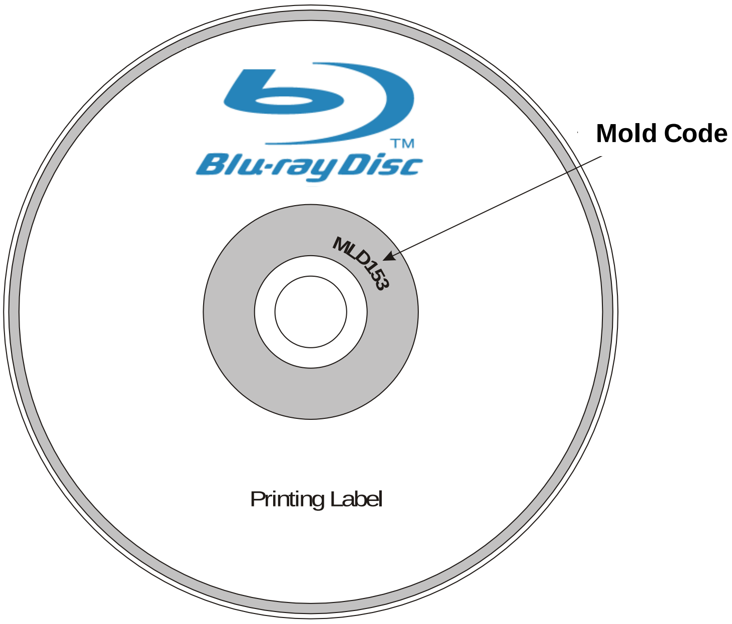


Fig. 14-1 Example of Mold Code

15. BCA

The zone between radius 21.0 mm and 22.2 mm is reserved to be used as an optional Burst-Cutting Area (BCA) defined by the application. The BCA is used to add unique information, such as the serial number, to the individual disc after completion of the manufacturing process. The BCA code can be written onto the disc by means of a high-power laser system.

The BCA code is recorded in CAV mode. Then BCA code is written as a series of low-reflectance stripes arranged in circumferential direction. Fig. 15-1 shows the schematic representation of the BCA.

At the early stage of DVD, BCA was recorded by using a YAG laser. But the YAG laser is expensive and the lifetime of YAG laser is not long enough. For the BCA code cutting of BD-ROM a cutting system using a high-power laser diode was used in order to make the low-cost manufacturing-system. Due to the limited power of the laser diode there remained some small dots reflective-layer material in the BCA code striped part. Those dots were the cause of HF noise in the reproduced BCA code signal. To remove the HF noise a low pass filter is used for the measurement system of BCA code and drives as shown in Fig. 15-2.

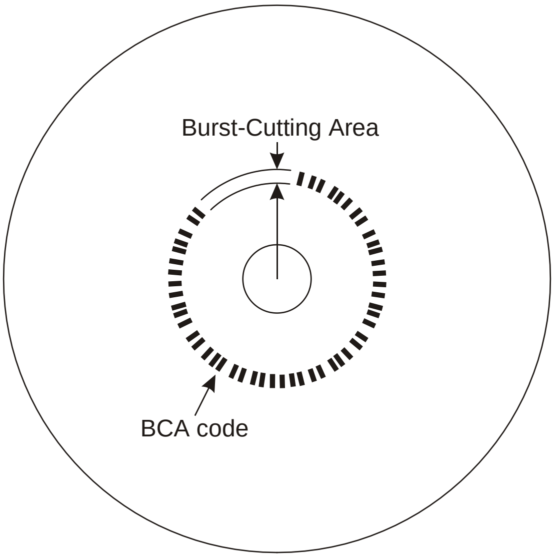


Fig. 15-1 Schematic representation of BCA

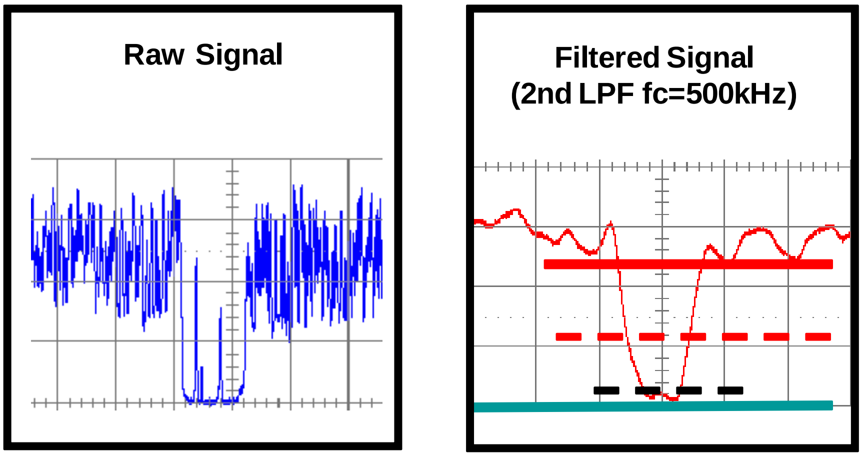


Fig. 15-2 BCA code measurement with LPF

16. Random Symbol Error Rate (RSER) measurement

ECC is designed to recover the correct data from the data damaged by defects. But ECC ability for correcting data in a disc is used not only for defects but also for the random error in a disc. In order to guarantee the ECC power for the user-oriented defects such as fingerprints and scratches, both the Random Symbol Error Rate (RSER) of a disc and defects should be specified. Roughly more than half of the ECC power is reserved for the user-oriented defects.

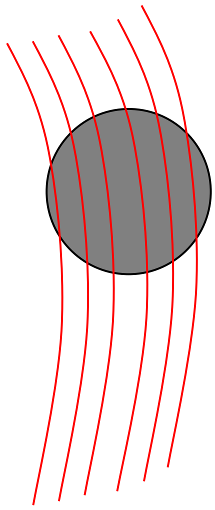


Fig. 16-1 Multiple error-count due to defect

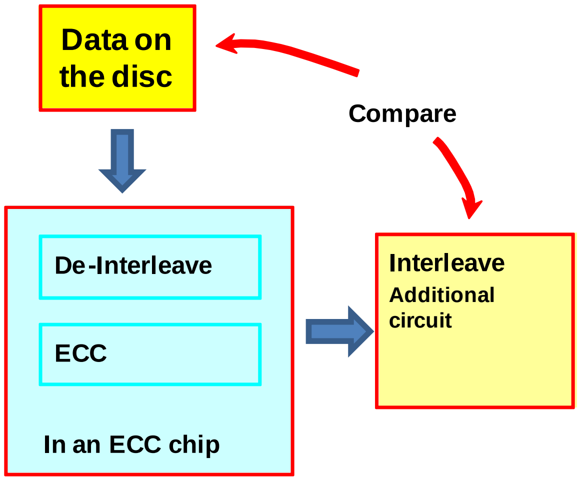


Fig. 16-2 ECC method for measuring RSER

The RSER for judging the system margin is 4.2 x 10^{-3}. This value is derived from the worst condition that all degradations of a disc and a drive occur simultaneously. Thus such a value is too high for the RSER value in which ECC works. The RSER of 1.0 x 10^{-3} was used for DVD. The value corresponds to a boundary condition + some degradation such as the worst radial-tilt with some tangential-tilt and some defocus in a rather bad drive. In the BD system a Viterbi decoder is located between the retrieved HF signal and an ECC circuit. The Viterbi decoder has the ability of the SNR improvement and it can reduce the RSER value below 1/10. The measurement circuit Limit Equalizer also can improve SNR as same as the Viterbi decoder and it also can reduce the RSER value below 1/10. For the RSER value of a disc measured after the Limit Equalizer a value of 2.0 x 10^{-4} is specified, which is 1/5 of 1.0 x 10^{-3}. In order to measure RSER the degradation due to the defects should be taken out. At the development stage the averaging in a large ECC Blocks was used for removing the effects of defects. But the averaging method was not enough for measuring such a low RSER value. In the inner radius there are 2.11 ECC Blocks within one rotation. If there is a large defects as shown in Fig. 16-1 then some 100 bytes errors are counted in every 2.11 ECC Blocks. That is the reason why the measured RSER jumped up around a defect.

Then it was decided to separate the defects and the RSER in the measurement method. Considering the ECC ability the allowed defects in an ECC Block (In the specification the block is called LDC Block.) is specified as 600 bytes in total and the maximum number of defects is specified as 7. From the measured RSER the consecutive errors longer than or equal 40 bytes are excluded. 40 bytes is the length of the 2 BIS (Burst-Indicating Subcode) + data between BIS (38 bytes) and it corresponds to the minimum-burst-error length BIS can detect. In order to detect the burst error correctly the ECC method measurement as shown in Fig. 16-2 is used. The correct data can be obtained after an ECC. By using additional circuit for the measurement the correct data after ECC are interleaved in order to get the correct-data allocation on a disc. It is compared with the data on a disc and the erroneous symbols are identified.

There are many cases where some correct bytes exist between the erroneous bytes. Fig. 16-3 shows an example of an error pattern. In order to judge the 40 bytes burst-error length the following procedure was specified. The burst starts after the correct bytes longer than or equal to 3 bytes. The error-length count continues if the correct-bytes length between error bytes is less than or equal to 2 bytes. The error-length count stops if there appear correct bytes longer than or equal to 3 bytes. Though the error length includes the correct bytes less than or equal 2 bytes, those correct bytes are excluded from the number of the erroneous bytes.

The errors longer than or equal to 40 bytes are excluded from both the numerator and the denominator of the RSER calculation. But the burst errors below 40 bytes are still included in the erroneous bytes. Although RSER is averaged over 10000 ECC Blocks, for the measurement 1000 Blocks averaging is allowed if the disc shows good RSER.

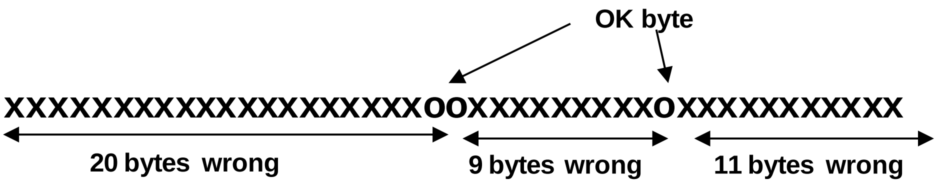


Fig. 16-3 Example of error pattern

17. Recommendation for maximum read-power of BD-ROM devices

In 2006, the BDMV application was extended to include BD-R and BD-RE, allowing a BD player to retrieve video from all disc types (i.e. BD-ROM/R/RE). Therefore, as a precaution to prevent possible damage to BD-R/RE discs, a recommendation for the maximum read-power was added in System Description Blu-ray Disc™ Read-Only Format Part1 Basic Format Specifications. In Clause 1.4.2 (Conformance of devices) it is recommended, that the maximum read-power* of BD-ROM devices must not exceed the read powers defined in the read-stability test of System Description Blu-ray Disc™ Rewritable Format Part1 or in the read-stability test of System Description Blu-ray Disc™ Recordable Format Part1. (* *Read power at intermediate speed can be obtained by interpolation*.)

18. Conclusion

In this BD-ROM White Paper the design considerations that played a role in determining the format parameters are explained. A short list of format parameters and format characteristics has been included. The technical experts of the Blu-ray Disc Association are confident that they have succeeded in realizing what they set out to achieve: defining a long-term solution for High-Definition movie / 4K UHD and/or HDR movie distribution on blue-laser discs.