

**Research
Report**

Development of CD-Rc: 120 mm Recordable Optical Disc Compatible with CD and DVD Based on a Newly Developed Inorganic Thin Film Multilayered Optical Memory

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Abstract

We have developed a new recordable optical disc, named CD-Rc, which can be recorded with commercially available CD-R drives equipped with 780 nm-laser diodes, and played with DVD-ROM drives equipped with 650 nm-laser diodes as well as with CD-ROM drives. By theoretical analysis we have found an appropriate shape of the pre-groove on the substrate to realize a system for tracking of the optical pickup which works well when a CD-Rc is inserted into any of the above-mentioned drives. The recording material used in the CD-Rc is a three-layered system

consisting of substrate/GeS₂/ZnS-SiO₂/Ge-doped Sn-Bi fabricated by successive sputter-deposition. The three-layered system shows moderate wavelength-dependence of reflectance from the visible to near-infrared ranges. We optimized the thickness of each layer to attain a reflectance high enough to enable playing at both 780 nm and 650 nm. This feature contrasts with the inability of a commercially available CD-R to be played by a DVD-ROM drive, because of very low reflectance at 650 nm.

Keywords

Optical disc, Recordable optical disc, Compact disc, Digital versatile disc, GeS₂, Eutectic alloy, Sputter deposition, Wavelength, Reflectance, Diffraction

1. Introduction

Development of optical discs to attain higher recording density has been remarkable in connection with the widespread use of digital video-recording systems as well as personal computers. One of the methods to increase recording density is to shorten the wavelength of the light incident onto the optical discs. After the Compact Disc (CD) system with a recording capacity of approximately 600 MB using a 780-nm laser diode came into general use, the Digital Versatile Disc (DVD) system was developed, attaining a recording capacity of approximately 4 GB higher than that of a CD. To realize this higher recording capacity, the DVD system utilizes a 650 nm-laser diode. Recently a new optical disc system using a 405 nm-laser diode was proposed, in order to attain a much higher recording capacity of approximately 25 GB.¹⁻⁴⁾

Recordable optical discs, on which users can record data but cannot erase it, are often used for small-scale distribution, image data storage, and archival use. CD-R,⁵⁾ which is the recordable-type disc of the CD family, employs an organic dye as the recording material. Because optical properties of the organic dye are highly dependent on wavelength, the reflectance of a CD-R at 650 nm or 405 nm is very low. Therefore, a CD-R cannot be played with a DVD-ROM drive equipped with a 650 nm-laser diode or, it will not be able to be played using a 405 nm-laser diode. This is a serious inconvenience, especially for archival use. DVD-R, which is the recordable-type disc of the DVD family, involves a similar inconvenience, because DVD-R also employs an organic dye.⁶⁾

One of the methods to get rid of the above-mentioned inconvenience of recordable optical discs employing organic dyes is the use of inorganic recording materials whose wavelength-dependences of optical properties are rather low. Many inorganic recording materials have been proposed for recordable optical discs utilizing phase change,⁷⁾ melting and hole formation,⁸⁾ dissolution of compounds,^{9, 10)} alloying or mixing of two materials,^{11, 12)} structure change of island films,¹³⁾ etc., triggered by intense laser irradiation.

We have recently developed a new optical

recording material: a three-layered system consisting of substrate/GeS₂/ZnS-SiO₂/Sn-Bi:Ge fabricated by successive sputter-deposition.¹⁴⁻¹⁶⁾ The recording mechanism utilized in the system is based on a redox reaction between GeS₂ and Sn-Bi:Ge (Ge-doped Sn-57wt.%Bi) triggered by the temperature rise caused by absorption of a recording laser. Both coloration in the GeS₂ layer and decrease in the reflectance of the Sn-Bi:Ge layer resulting from the reaction contribute to the decrease in the reflectance of the system. The ZnS-SiO₂ layer is inserted for suppression of unexpected reactions between the GeS₂ layer and the Sn-Bi:Ge layer. Ge is doped in Sn-Bi for improvement of durability. We have succeeded in recording and playing image data on optical discs adopting the newly developed three-layered system with commercially available CD-R drives.¹⁴⁾

The substrate/GeS₂/ZnS-SiO₂/Sn-Bi:Ge system shows moderate wavelength-dependence of reflectance from the visible to near-infrared ranges. Therefore, it is a candidate for an optical recording material which can be recorded and played at various wavelengths in a wide range. In this study, we attempt to realize a new optical disc which can be recorded with CD-R drives equipped with 780 nm-laser diodes, and can be played with DVD-ROM drives equipped with 650 nm-laser diodes as well as CD-ROM drives. By theoretical analysis we found an appropriate shape of the pre-groove formed on the substrate to realize a system for tracking of the optical pickup that works well when the optical disc has been recorded with CD-R drives and played with DVD-ROM drives as well as CD-ROM drives. Then we fabricated optical disc samples using substrates having the pre-grooves of the obtained shape, in order to examine their performance. We also examined how the optical disc performance depended on the thickness of each layer, so as to find the optimal thickness.

2. Optimization of the pre-groove shape

2.1 Tracking signals

A pre-groove is spirally formed on a substrate for a recordable optical disc. When an optical disc is recorded or played, an optical pickup tracks along the center of the pre-groove by monitoring its

location. Several kinds of signals are used for the location monitoring for the tracking. Among them, "radial contrast (RC)" and "radial push-pull signal (PP)" are the most important. When an optical disc is inserted into a drive, the pickup seeks the pre-groove and moves to be located beneath the pre-groove, as shown in **Fig. 1**. RC is a signal for determining whether the pickup is located beneath the pre-groove or beneath the land. After finding the pre-groove, the pickup tracks along the center of the pre-groove. PP is the signal for detecting the displacement of the pickup from the center of the pre-groove.

The configuration of the optical pickup is schematically illustrated in **Fig. 2**, where I_a and I_b denote the signal intensities from the two photodetectors. Groove reflectance at an unrecorded area ($R_g[u]$) of the recordable-type CD is defined as follows and subjected to the following requirement^{5,17)}:

$$R_g[u] = (I_a[u] + I_b[u])_{\text{groove}}, \dots\dots\dots(1)$$

$$R_g[u] > 65\%, \dots\dots\dots(2)$$

where subscript "groove" means the value with the laser beam being incident onto the center of the groove, and "[u]" means the value at an unrecorded area. Land reflectance at an unrecorded area ($R_l[u]$) is defined in a similar manner. The intensity of RC (I_{RC}) of the recordable-type CD is defined as follows and subjected to the following requirement:

$$I_{RC} = 2 (R_l[u] - R_g[u]) / (R_l[u] + R_g[u]), \dots\dots\dots(3)$$

$$I_{RC} > 0.05. \dots\dots\dots(4)$$

The intensity of PP (I_{PP}) is derived from the distortion of the beam pattern of the light reflected from the optical disc. I_{PP} is defined as follows and subjected to the following requirement:

$$I_{PP}[a] = \{ (I_a[u] + I_a[r]) - (I_b[u] + I_b[r]) \}_{\Delta y = 100\text{nm}} / \{ 2 (I_a[u] + I_b[u]) \}_{\Delta y = 0}, \dots\dots\dots(5)$$

$$0.09 > I_{PP}[a] > 0.04, \dots\dots\dots(6)$$

where subscript " $\Delta y = 100\text{nm}$ " (" $\Delta y = 0$ ") means the value with the center of the incident laser beam located at 100 nm (0 nm) from the pre-groove center, and "[r]" means the value at a recorded area. $I_a[r]$, $I_b[r]$ are too complicated for exact calculation, because they are affected by the shape of the recording pit. Therefore, $I_a[r]$, $I_b[r]$ were assumed to be 0.1 times as large as $I_a[u]$, $I_b[u]$, respectively, because the groove reflectance at a recorded area ($R_g[r]$) of an optical disc using the three-layered system was found to be approximately equal to 0.1 times $R_g[u]$ ¹⁴⁾ (See Fig. 8). Under this assumption, the requirement for $I_{PP}[s]$ shown in Eq. (6) is equivalent to the following expressions:

$$I_{PP}[u] = (I_a[u] + I_b[u])_{\Delta y = 100\text{nm}} / (I_a[u] + I_b[u])_{\Delta y = 0}, \dots\dots\dots(7)$$

$$0.164 > I_{PP}[u] > 0.073. \dots\dots\dots(8)$$

We calculated I_{RC} and $I_{PP}[u]$ to find an appropriate pre-groove shape which satisfies the requirements expressed by Eqs. (4) and (8). We also calculated the dependence of $R_g[u]$ on the pre-groove shape. When the values from a CD-ROM drive were calculated, a wavelength of 780 nm and a numerical aperture (NA) of the objective lens of 0.45 were used. As for DVD-ROM drives, a wavelength of 650 nm and an NA of 0.35-0.4 were used.^{18,19)}

2.2 Modeling

The structure of the cross section of the optical disc using the three-layered system was modeled as

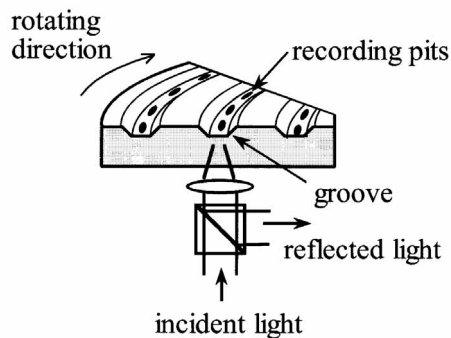


Fig. 1 Schematic illustration of a recordable optical disc system.

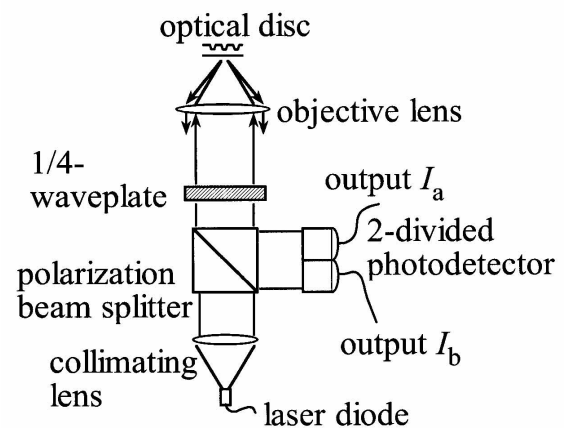


Fig. 2 Schematic illustration of an optical pickup.

shown in **Fig. 3**. The surface of the substrate was defined by the following expression using three independent parameters: groove width (w_g), groove depth (d_g), and slope width (w_s);

$$z = -d_g/2 \{ \tanh[1.09861 (|y| - w_g/2) / w_s] + 1 \} \quad (|y| < 800 \text{ nm}). \quad (9)$$

The optical pickup was modeled as follows to calculate the tracking signal intensities. The details of the formulation are described elsewhere.^{20, 21)}

(1) The configuration of the optical pickup is simplified as shown in Fig. 2.

(2) The light going from the laser diode onto the optical disc and returning from the optical disc to the photodetectors is treated according to the scalar diffraction theory where polarization dependence is ignored ($z > 0$ in Fig. 3). In the optical disc, the light propagation is analyzed by the vector diffraction theory ($z < 0$ in Fig. 3). Maxwell equations in the three-layered structure of the optical disc are rigorously solved to obtain the diffraction efficiency of the optical disc.²²⁾

(3) The objective lens acts as an ideal Fourier transform lens with an infinite radius for light incident onto the optical disc, because the actual focal length (several millimeters) is much larger than the groove width and beam radius on the optical disc.

(4) The objective lens is replaced with a combination of an ideal Fourier transform lens and an aperture corresponding to NA of the objective lens for the light reflected from the optical disc.

I_{RC} or $I_{PP}[u]$ were confirmed to depend very slightly on the thicknesses of the three layers on the substrate, although I_a , I_b , and hence $R_g[u]$ were dependent on them. Therefore, the thicknesses of the GeS_2 layer and the ZnS-SiO_2 layer were set to be zero, and the Sn-Bi:Ge layer was replaced with an ideal mirror layer of 100 % reflectance. In this case the calculated value of $R_g[u]$ corresponds to the ratio of the groove reflectance of the actual optical disc to reflectance of the same three-layered structure on a flat substrate.

$R_g[u]$, I_{RC} , and $I_{PP}[u]$ were confirmed to be scarcely affected by w_s within the range of 100 nm to 150 nm. Therefore w_s was fixed at 135 nm.

2.3 Results and discussion for optimization of the pre-groove shape

Figure 4(a) shows the calculated results for $R_g[u]$, I_{RC} , and $I_{PP}[u]$ from a CD-ROM drive. $R_g[u]$ was found to decrease with increasing d_g , whereas it was found to depend only slightly on w_g . I_{RC} increased with increasing d_g , and decreased with increasing w_g . $I_{PP}[u]$ increased with d_g , and also increased with w_g . **Figures 4(b) and (c)** show the calculated results for DVD-ROM drives. $R_g[u]$, I_{RC} , and $I_{PP}[u]$ were more significantly dependent on d_g than were those from a CD-ROM drive. The dependences of $R_g[u]$, I_{RC} , and $I_{PP}[u]$ on w_g were similar to those for a CD-ROM drive when d_g was smaller than 50 nm.

Figure 5 shows the condition for d_g and w_g where both the requirements in Eqs. (4) and (8) are satisfied by values of d_g and w_g in the hatched areas.

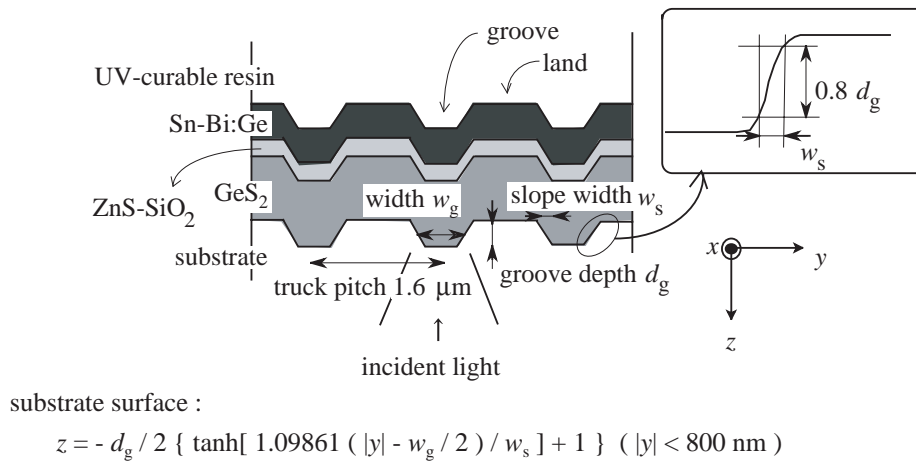


Fig. 3 Modeling of the cross-section of the newly developed optical disc.

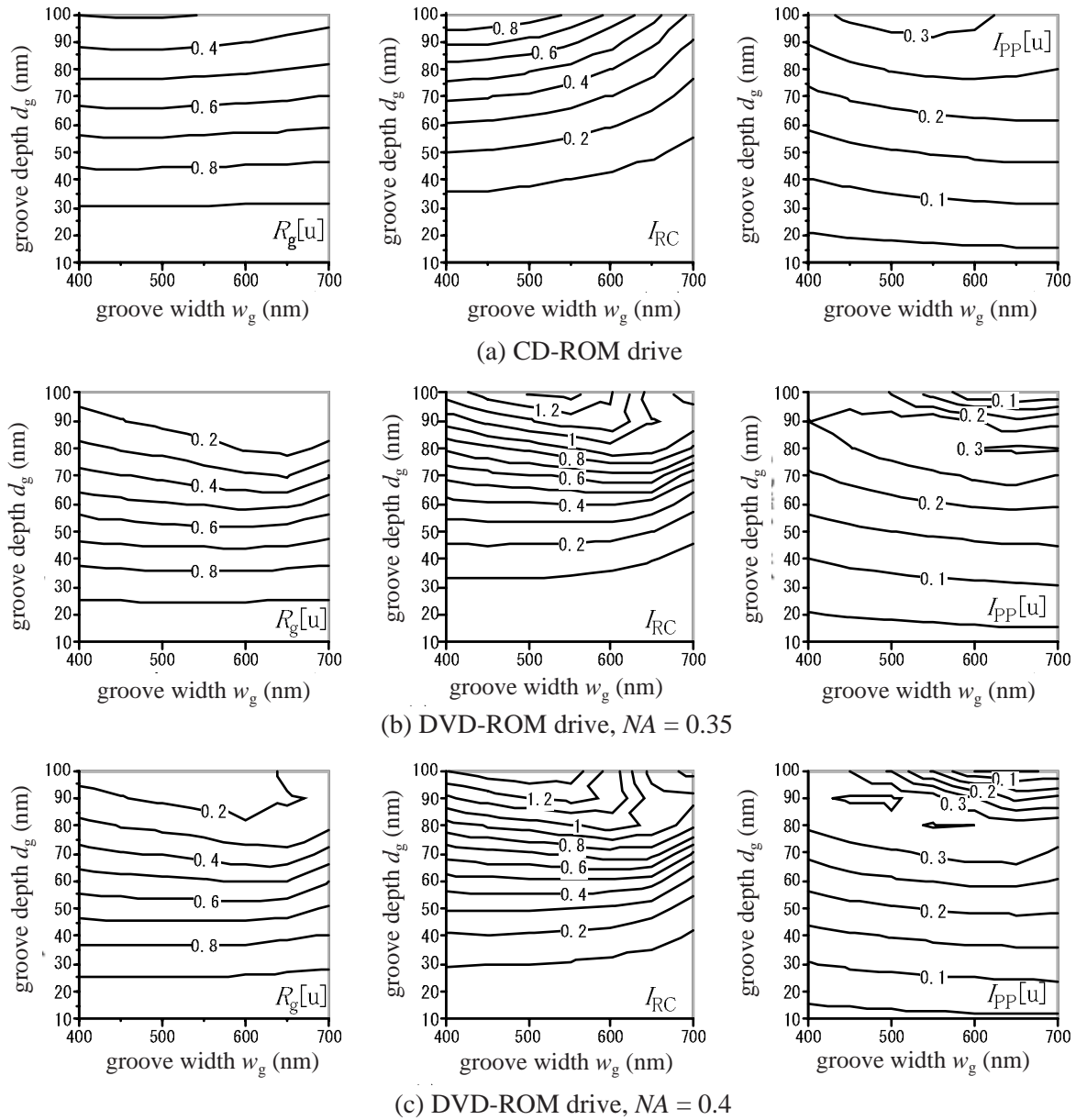


Fig. 4 Calculated results of groove reflectance ($R_g[u]$), radial contrast intensity (I_{RC}), and radial push-pull signal intensity ($I_{PP}[u]$): (a) from a CD-ROM drive ($\lambda = 780$ nm, $NA = 0.45$), (b), (c) from DVD-ROM drives ($\lambda = 650$ nm, $NA = 0.35, 0.4$).

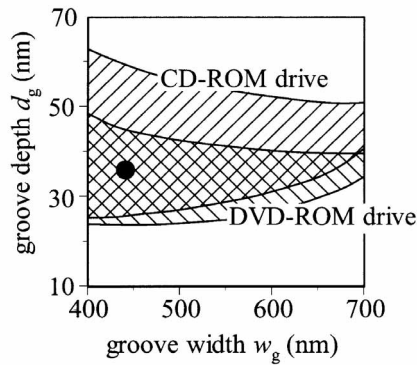


Fig. 5 Condition for groove width (w_g) and groove depth (d_g) to satisfy the requirements. The values $w_g = 440$ nm, $d_g = 36$ nm employed in CD-Rc are shown by a closed circle.

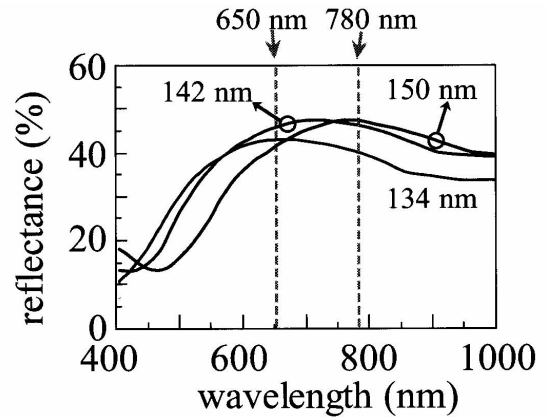


Fig. 6 Reflectance spectra of the three-layered structures on flat substrates.

The lower limit of d_g at a certain w_g is given from the requirement for I_{RC} , whereas the upper limit is given from the upper limit of $I_{PP}[u]$. Because $R_g[u]$ is scarcely affected by w_g , we should consider only I_{RC} and $I_{PP}[u]$ in choosing an appropriate w_g value. Because the tolerance for d_g is large when w_g is small, a rather narrow groove: $w_g = 440$ nm, was employed for the new optical disc. When w_g equals 440 nm, both the requirements for CD-ROM drives and those for DVD-ROM drives are satisfied using a value of d_g within the range from 25 nm to 46 nm. The median of the range, $d_g = 36$ nm, was employed for the new optical disc.

3. Optimization of the thicknesses of the three layers

3.1 Experimental

The optical disc samples were fabricated by depositing the GeS_2 layers, the ZnS-SiO_2 layers, and the Sn-Bi:Ge layers successively on polycarbonate substrates, followed by overcoating with a UV-curable resin. The substrates, measuring 120 mm in diameter with the pre-grooves having a groove width $w_g = 440$ nm and a groove depth $d_g = 36$ nm, were fabricated by injection molding. "Cube-Duo" optical disc coater (Balzers A. G.) was used for sputter-deposition of the three kinds of layers with a sputtering gas of argon. The GeS_2 layers and the ZnS-SiO_2 layers were deposited by RF magnetron sputtering. The Sn-Bi:Ge layers were deposited by DC magnetron sputtering. After the three layers were deposited, a UV-curable resin was spin-coated on the Sn-Bi:Ge layer, followed by UV irradiation. The same three-layered structures were also deposited on flat substrates for detailed investigation.

The reflectance spectra of the samples on flat substrates were measured with a spectrophotometer. The basic recording performance of the optical disc samples was evaluated with an optical disc tester equipped with a 780 nm-laser diode and an objective lens of NA 0.53 (NAKAMICHI, OMS-2000). A rectangular wave signal with a duty ratio of 50% was used. A constant linear velocity of 2.8 m/s (double speed) and a modulation frequency of 400 kHz, or 5.6 m/s (four-times speed) and 800 kHz were used. $R_g[u]$ of the optical disc samples was

measured with the optical disc tester. The dependence of carrier to noise ratio (CNR) on the recording laser power was measured. "Modulation (Mod)", which is defined as follows:

$$Mod = (R_g[u] - R_g[r]) / R_g[u], \dots\dots\dots(10)$$

was also measured as a function of the recording laser power. "Recordable laser power (P_r)" was defined as the recording laser power at which Mod becomes higher than 60 % and CNR becomes higher than 47 dB, because Mod and CNR of the recordable type of CD are required to become higher than 60 % and 47 dB, respectively, at a certain recording laser power between 8 and 11 mW and a linear velocity of 2.8 m/s.^{5, 17)}

The optical disc samples were examined to determine whether they could be recorded with CD-R drives and whether they could be played with CD-ROM drives and DVD-ROM drives. Several kinds of commercially available drives from different suppliers were used for the examination.

3.2 Results and discussion for optimization of the thicknesses of the three layers

Figure 6 shows the reflectance spectra of the samples on flat substrates with different GeS_2 layer thicknesses ($d[\text{GeS}_2]$). Because the spectra were roughly the superposition of the reflectance spectrum of the Sn-Bi:Ge layer itself and the interference patterns, the peak locations depended on $d[\text{GeS}_2]$. Here the thicknesses of the ZnS-SiO_2 layer ($d[\text{ZnS-SiO}_2]$) and the Sn-Bi:Ge layer ($d[\text{Sn-Bi:Ge}]$) were set to be 1 nm and 60 nm, respectively; both of them were confirmed to scarcely affect the peak locations. We have already confirmed that the optical disc using the three-layered system with $d[\text{GeS}_2]$ of 150 nm can be recorded and played with CD-R drives.¹⁴⁾ However, it could not be played with DVD-ROM drives, because the reflectance at 650 nm was low. Higher reflectance at both 780 nm and 650 nm is necessary for the present purpose. Therefore, $d[\text{GeS}_2]$ of 142 nm was employed for the new optical disc.

Figure 7(a) shows the dependences of $R_g[u]$ and P_r on $d[\text{ZnS-SiO}_2]$. When $d[\text{ZnS-SiO}_2]$ was 0.5 nm or 1 nm, recording on the disc samples with CD-R drives and playing with CD-ROM drives were possible. P_r for 1 nm was the same as that for 0.5 nm, whereas $R_g[u]$ for 1 nm was better than that for

0.5 nm, showing a slightly higher value. Therefore, $d[\text{ZnS-SiO}_2]$ of 1 nm was employed for the new optical disc. $R_g[u]$ for 2 nm was the same as that for 1 nm. This result indicates that 1 nm is thick enough to suppress the redox reaction between the GeS_2 layer and the Sn-Bi:Ge layer during the deposition processes.

Figure 7(b) shows the dependences of $R_g[u]$ and P_r on $d[\text{Sn-Bi:Ge}]$. When $d[\text{Sn-Bi:Ge}]$ was 56 nm and below, the optical disc samples could not be recorded with CD-R drives, because of too low $R_g[u]$. When $d[\text{Sn-Bi:Ge}]$ was 68 nm recording was not possible, because of too high P_r . The optical disc samples with $d[\text{Sn-Bi:Ge}]$ of 60 nm could be played with all of the CD-ROM drives used in the examination. Those with $d[\text{Sn-Bi:Ge}]$ of 64 nm could be played only with certain drives, although the recording sessions with CD-R drives were

successfully completed. These results show that recording and playing were possible with all of the drives when $d[\text{Sn-Bi:Ge}]$ was around 60 nm. Therefore, $d[\text{Sn-Bi:Ge}]$ of 60 nm was employed for the new optical disc.

We named the newly developed optical disc "CD-Rc". The relations between Mod and CNR , and the recording laser power of a CD-Rc is shown in Fig. 8.

We confirmed that computer data files can be recorded on a CD-Rc with CD-R drives with double speed and four-times speed. The files could be read with CD-R drives, CD-ROM drives, and DVD-ROM drives. Movie data files were also used for examination. They could be recorded on a CD-Rc with CD-R drives and could be played smoothly with CD-R drives, CD-ROM drives, and DVD-ROM drives. Recording and playing were possible

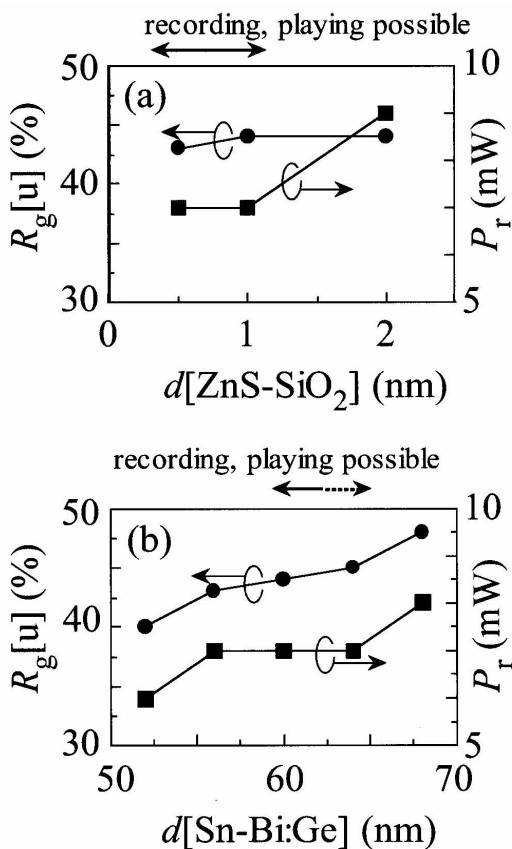


Fig. 7 Groove reflectance at an unrecorded area ($R_g[u]$) and "recordable laser power (P_r)" measured at a constant linear velocity of 2.8 m/s: (a) $d[\text{GeS}_2] = 142$ nm, $d[\text{Sn-Bi:Ge}] = 60$ nm, (b) $d[\text{GeS}_2] = 142$ nm, $d[\text{ZnS-SiO}_2] = 1$ nm.

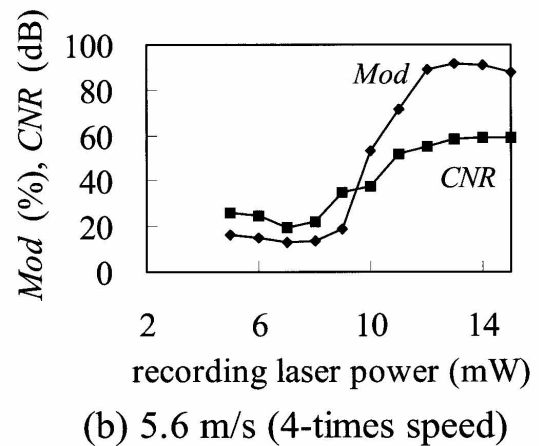
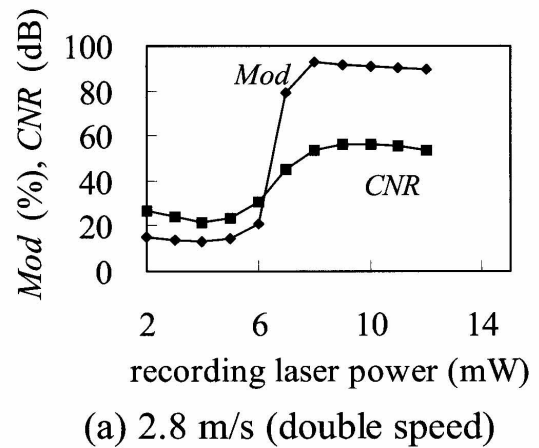


Fig. 8 Relations between "modulation (Mod)" and carrier to noise ratio (CNR), and recording laser power of CD-Rc.

with all the commercially available drives used in the examination.

4. Practical application of CD-Rc for development of DVD-navigation software

We applied CD-Rc to development of software for DVD-navigation systems and reduced development cost.

In the development of the software, a new program constructed on a workstation is installed into the FLASH-ROM in the DVD-navigation system and is examined to determine whether it runs well. The DVD-navigation drive can play a DVD-R but cannot play a commercially available CD-R, because, in order to reduce the price, it is not equipped with a 780 nm-laser diode in addition to a 650 nm-laser diode. Therefore, two methods for installing a new program have been followed. One is the use of a DVD-R, which is several times more expensive than a CD-R. The other is modification of the DVD-navigation system to be connected with a CD-ROM drive. Both of these methods increased development cost.

It was confirmed that a new program recorded on a CD-Rc could be installed into the FLASH-ROM by playing the CD-Rc with the DVD-navigation drive. Several hundreds pieces of CD-R a month were produced using "Cube-Duo" and used for the development of the DVD-navigation software. The use of CD-Rc enabled the simplest method, installing a new program with no modification on the DVD-navigation system, which involves no additional cost.

5. Conclusion

We have developed a new recordable optical disc, named CD-Rc, which uses the substrate/ GeS_2 / ZnS-SiO_2 /Ge-doped Sn-Bi system. Optimization of the thickness of each layer was necessary to attain reflectance high enough to enable playing at both 780 nm and 650 nm, and to attain adequate recording sensitivity. We found an appropriate shape of the pre-groove on the substrate used in the CD-Rc to obtain adequate intensities of the tracking signals when a CD-Rc was inserted into any of CD-R drives, CD-ROM drives, and DVD-drives. We utilized the feature of CD-Rc that it can be recorded

with CD-R drives and can be played with DVD-ROM drives for the development of DVD-navigation software.

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References

- 1) Ichimura, I., Masahara, S., Nakano, J., Kasami, Y., Yasuda, K., Kawakubo, O. and Osato, K. : SPIE Proc., **4342**(2002), 168
- 2) Kuijper, M., Ubbens, I. P., Spruijt, L., Matthijs ter Meulen, J. and Schep, K. : SPIE Proc., **4342**(2002), 178
- 3) Furumiya, S., Minamino, J., Miyashita, H., Nakamura, A., Shouji, M., Ishida, T. and Ishibashi, H. : SPIE Proc., **4342**(2002), 186
- 4) "Blu-ray Disc License Site", available from <<http://www.blu-raydisc.info/>>
- 5) Hamada, E., Shin, Y. and Ishiguro, T. : SPIE Proc., **1078**(1989), 80
- 6) Hamada, E., Takagishi, Y., Yoshizawa, T., Fujii, T., Negishi, R. and Nakajima, T. : Jpn. J. Appl. Phys. **39**(2000), 785
- 7) Takenaga, M., Yamada, N., Nishiuchi, K., Akahira, N., Ohta, T., Nakamura, S. and Yamashita, T. : J. Appl. Phys., **54**(1983), 4376
- 8) Horie, M., Tamura, T., Ohgaki, M. and Yoshida, H. : J. Appl. Phys., **75**(1994), 2680
- 9) Hsu, W.-C., Tseng, M.-R., Tsai, S.-Y. and Kuo, P.-C. : Jpn. J. Appl. Phys., **42**(2003), 1005
- 10) Hosoda, Y., Izumi, T., Mitsumori, A., Yokogawa, F., Jinno, S. and Kudo, H. : Jpn. J. Appl. Phys., **42**(2003), 1040
- 11) Matsubara, M., Ohkawa, H., Yoshimaru, T., Yoshida, N. and Koyahara, S. : Jpn. J. Appl. Phys., **32**(1993), 5234
- 12) Inoue, H., Mishima, K., Aoshima, M., Hirata, H., Kato, T. and Utsunomiya, H. : Jpn. J. Appl. Phys., **42**(2003), 1059
- 13) Baba, K., Ohkuma, Y., Yonezawa, T. and Miyagi, M. : Appl. Opt., **40**(2001), 2796
- 14) Kato, N., Fukano, T., Takeda, Y., Takeichi, A. and Motohiro, T. : R&D Review of Toyota CRDL **38-3**(2003), 21
- 15) Fukano, T., Kato, N., Takeda, Y., Takeichi, A. and Motohiro, T. : R&D Review of Toyota CRDL, **38-3**(2003), 8
- 16) Takeichi, A., Takeda, Y., Fukano, T., Kato, N. and Motohiro, T. : R&D Review of Toyota CRDL, **38-3**(2003), 14
- 17) "Recordable Compact Disc (CD-R) Systems", available from <http://www.y-adagio.com/public/standards/tr_cdr/tr_cd-r.htm>, (in Japanese)

- 18) Tsuchiya, Y., Kajiyama, S., Kano, T., Matsushita, Y. and Ichiura, S. : Jpn. J. Appl. Phys., **36**(1997), 481
- 19) Hayashi, H., Yamamoto, H., Anzai, J., Kamei, T., Mizuno, S., Tanaka, Y. and Yamagata, M. : Jpn. J. Appl. Phys., **40**(2001), 1760
- 20) Murakami, M. : Trans. IEICE, **J67-C**(1984), 219, (in Japanese)
- 21) Ooki, H. : Optik, **89**(1991), 15
- 22) Chandezon, J., Dupuis, M. T., Cornet, G. and Maystre, D. : J. Opt. Soc. Am., **72**(1982), 839
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