Media Technologies of 40 GB Dual-Layer Rewritable Phase-Change Recording for HD DVD System

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ABSTRACT

We have successfully demonstrated feasibility of a single-side dual-layer rewritable HD DVD media having a larger user data capacity of 40 GB (20 GB/layer) for the optical system with the NA of 0.65 and the wavelength of 405 nm, and light incidence on 0.6-mm-thick substrate having the land and groove format. Two kinds of more accurate analysis technologies were applied to the development of the higher density rewritable HD DVD media. One is a thermal simulation and design technology of the media utilizing an accurate measurement of thermo-physical properties for thin films using thermo-reflectance method and another one is a high sensitivity analysis technology using the synchrotron orbital radiation, in particular, XAFS (X-ray Absorption Fine Structure) and HX-PES (Hard X-ray Photoelectron Spectroscopy) method. In the thermal analysis of the media, boundary thermal resistance between thin films plays an important role. The interface layer changes the electronic state of the recording layer and promotes crystallization acceleration with only slightly affecting the local structure of the atomic arrangement according to the analysis of XAFS and HX-PES. We speculate that this effect is an important factor for the high-speed crystallization. These findings are useful in understanding the high-speed phase-change mechanism in the optical recording media. As a result, the dual-layer rewritable HD DVD media with larger capacity has been achieved and even high speed operation rate will be realized based on these technologies.

Key words: dual-layer rewritable HD DVD media, 40 GB, more accurate thermal analysis, HX-PES, XAFS, interface layer, phase-change recording material, GeSbTe, GeBiTe

1. INTRODUCTION

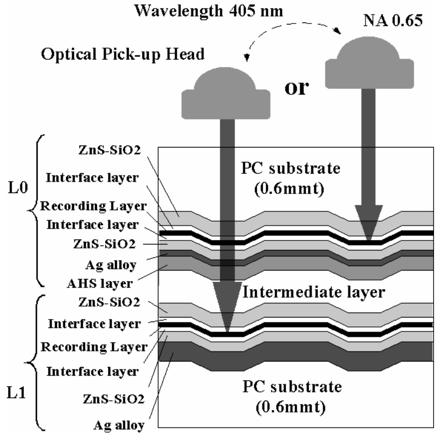
We have already demonstrated the feasibility of both single-layer rewritable media having a data capacity of 20 GB and dual-layer phase change recording media with 36 GB (18 GB/layer) user data capacity at the data transfer rate of 36.55 Mbps (1X) for the HD DVD system [1,2]. The higher density rewritable HD DVD system has the numerical aperture (NA) of 0.65 and the wavelength of 405 nm, and light incidence on 0.6-mm-thick a polycarbonate (PC) substrate having the land and groove (L/G) format. In addition, the recording characteristics of higher data transfer rate of 2X or more have been successfully demonstrated for both single-layer and dual-layer rewritable HD DVD media [3,4]. A feature of single-layer rewritable disc having 20 GB user data capacity, which is called HD DVD-RAM, is a low-to-high signal polarity (L-to-H, *i.e.*, Ra>Rc where Ra and Rc show the reflectivity of amorphous and crystalline states, respectively) [1]. In this media, the track pitch (TP) for the substrate was designed at 0.34 um. On the other hand, the dual-layer disc having 36 GB data capacity has a high-to-low polarity (H-to-L, *i.e.*, Ra<Rc) by using the TP of 0.36 um along with the same bit pitch (BP) and the L/G format as HD DVD-RAM [1, 2]. However, it is better that the dual-layer media has the same TP as that of HD DVD-RAM in order to obtain the compatibility of the optical system with HD DVD-RAM. The capacity of dual-layer media grows up to 40 GB (20 GB/layer) as a result of reduction of TP form 0.36 to 0.34 um with BP being kept the same. Such larger capacity is desired because it enables longer recording times for HDTV. Since there has always been a strong demand for high speed recording rewritable and write once type DVDs or CDs, we expect that the next step for the rewritable HD DVD is also to realize high speed recording.

In this paper, we describe the media technologies of 40 GB dual-layer rewritable phase-change recording media for HD DVD system and the analysis results of influence of interface layer to phase-change recording material to clarify the high-speed phase-change mechanism.

2. FILM STRUCTURE AND THERMAL ANALYSIS

2.1. DESIGN OF FILM STRUCTURE

Figure 1 shows the cross sectional view of the dual-layer rewritable HD DVD media. The substrates used in this study were 0.6-mm-thick PC substrates having the L/G format. Layer 0 (L0) has seven films and Layer 1 (L1) has six films. The dual-layer media with 40 GB has the H-to-L polarity similar to the media with 36 GB. For L0, less than 10-nm-thick recording film and about 10-nm-thick Ag alloy were adopted in order to obtain transmittance of more than 50 %. In addition, an oxide material without optical absorption as the interface layer to enhance erasability (ER) of the media was used and located on both sides of the recording film. We adopted a GeTe rich GeTe-Sb_2Te_3 (GeSbTe : GST) pseudo-binary alloy as the recording layer at data transfer rate of 1X. For a high-speed phase-change recording material a GeTe rich GeTe-Bi_2Te_3 (GeBiTe : GBT) pseudo-binary alloy was applied instead of GST in the media, because the crystallization speed of GBT is higher than that of GST[3,4]. GBT is a system in which Sb of GST was completely substituted with Bi.



*AHS layer : Additional Heat Sink layer

Fig. 1 Cross-sectional view of the dual-layer rewritable HD DVD media.

2.2. CONDITIONS OF THERMAL ANALYSIS OF THE MEDIA

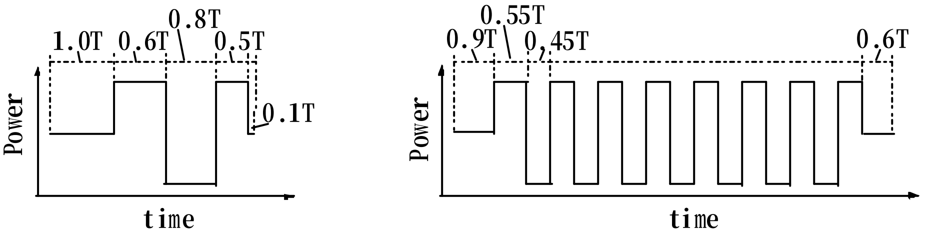
More accurate thermal simulation technology, which includes accurate measurement of thermo-physical properties for thin films using pico-second thermo-reflectance method[5-7], was used for the design of film stack together with optical one in this study, in order to avoid cross-erase (XE) problem. Three dimensional and non steady-state heat conduction equations were solved numerically based on finite element method (FEM). Initial and boundary temperatures of analyzed model were assumed 25 °C. In the analysis of the media, boundary thermal resistance between thin films and accurate thermo-physical properties for thin films play important roles for accurate estimation for temperature distribution of the media, because it is difficult to measure thermal properties of thin films having the thickness of the order of ten nanometers used for the media. Thermal analysis of the media have been carried out on both land and groove and both L0 and L1 having the TP from 0.4 to 0.32 um. Simulation conditions were assumed similar to actual recording conditions of the media as summarized in Table I. The moving direction of the media is perpendicular to text plane in Fig. 1. We assumed that the linear velocity of the disc rotation is 5.6 m/s as well as actual media with data transfer rate of 1X, and the distribution of heat source is Gaussian as laser beam intensity on the recording film. The laser irradiation pattern during the amorphous mark writing process assumed two monotone patterns, short marks (3T), and long marks (9T) as typical cases. Both 3T and 9T write strategies using multi pulse trains shown in Fig. 2 were used for each numerical calculation. The spatial temperature distributions at the highest temperature in the media were compared with several conditions. Those are instants when the temperatures of recording layers reach the maximum temperature at each condition. It is the moment that the last pulse is turned off in each case.

Table I. Summarization of calculation model used for thermal analysis.

Method	FEM(3-D, non steady-state)
Laser spot and heat source	Gaussian
Linear velocity	5.6 m/s (the disc rotation), 1X
Initial and boundary temperatures	25 °C
TP	0.4, 0.36, 0.34, 0.32 um
Layer	L0, L1
Track	Land, Groove
Mark length	3T (Short mark), 9T (Long mark)

2.3. THERMAL DESIGN OF HIGH DENSITY DUAL-LAYER REWRITABLE HD DVD MEDIA

Figure 3 shows the results of L0 and L1 with TP of 0.34 um exposed to 9T strategy at land track, for example. The temperature on the edge of the track which is adjacent to the recorded track was obtained from such calculations. The relation of the temperature and TP for both land and groove and for both L0 and L1 was shown in Fig. 4. The temperatures of the nearest-neighbor track edge with TP of 0.34 um do not rise up more than the crystallization temperature (Tc) of the recording layer for all conditions. The Tc of GST that we used is about 180 °C. This result suggests that the media with TP of 0.34 um, the dual-layer media with 40 GB, is possible from the viewpoint of thermal design. The temperature of adjacent track with TP of 0.36 um or more is suppressed below the Tc of our recording film. Moreover, the temperature of adjacent track with TP of 0.32 um does not increase up to the Tc of ours. It is expected that the optimization of the film design or using another recording material with higher Tc enables higher density media. This result gave us the motive for developing the high density media. So, we tried to improve the capacity for dual-layer rewritable HD DVD media.



(a) short mark (3T) (b) long mark (9T)

Fig. 2 Write strategy of the recording of marks used for thermal analysis.

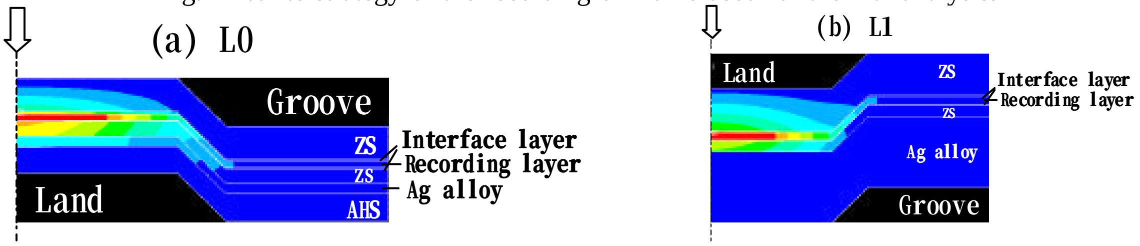


Fig. 3 Temperature distributions of the L0 and L1 having the TP of 0.34 um illuminated 3T mark on land track.

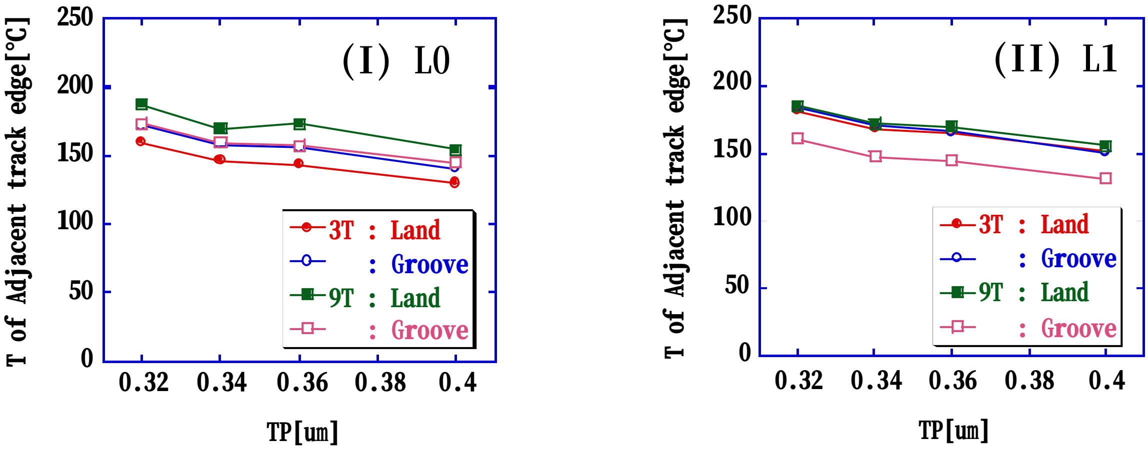


Fig. 4 The relation of the temperature and TP both land and groove and both L0 and L1.

3. EXPERIMENTS

3.1. FABRICATION AND EVALUATION CONDITIONS OF THE 40GB DUAL LAYER MEDIA

We fabricated the dual-layer rewritable HD DVD media with 40 GB based on the above analysis and design. Film stacks of L0 and L1 were sputter-deposited individually on separate 0.6-mm-thick PC substrates by a manufacturing scale sputtering equipment (OCTAVA-II : Shibaura Mechatronics Corp). Two film stacks were bonded using the ultraviolet curing (UV) resin with a bonding machine for DVD (Cielo : Shibaura Mechatronics Corp.), which is commercially available for the mass production of the current DVDs including DVD-9. This UV resin layer functions as an optical separation layer between two information layers.

The recording characteristic of the media was evaluated as shown in Table II. The same TP and BP as the recording condition of HD DVD-RAM are used for 40 GB. The format efficiency is assumed to be 83 %. The simulated bit error rates (SbER) and partial-response signal-to-noise ratio (PRSNR) were measured. These properties were evaluated on the track at the center after overwriting random data 10 times on neighboring 5 tracks, which means that the data includes cross-talk (XT) and XE.

Table II. Recording conditions.

User capacity	40 GB (20 GB/layer)
User transfer rate	36.55 Mbps (1X)
Laser wavelength	405 nm
NA of objective lens	0.65
Thickness of substrate	0.6 mm
Track pitch	0.34 um (Land & Groove)
Data bit length	0.13 um/bit
Minimum mark length	0.173 um
Channel clock frequency	64.8 MHz
Modulation code	ETM & RLL(1,10)
Data detection method	PR(1,2,2,2,1)ML

3.2. ANALYSIS OF HIGH-SPEED CRYSTALLIZATION MECHANISM

High speed recording has always been a strong demand for storage devices. The phase-change recording material, interface layer material and interaction between them affect high speed phase-change for the media. To clarify interaction between phase-change recording material and interface layer is useful to find out the high-speed phase-change mechanism. On the other hand, we use even thinner phase-change recording material films of around 10 nm or less for rewritable HD DVD media. Physical properties are known to be different between the bulk and the thin film depending on the film thickness. Therefore we should understand the behavior of such thinner films. The HX-PES (Hard X-ray Photoelectron Spectroscopy) 8-10) and XAFS (X-ray Absorption Fine Structure) 11) were performed in order to analyze the influence of the interface layer to phase-change recording material for the chemical and electronic state in addition to the local structure, at BL47XU 8-10) and BL16B2 11) of SPring-8, Hyogo, Japan, respectively. The incident x-ray is generated by synchrotron orbital radiation for both experiments. Table III and IV are summaries of analysis equipments and conditions.

It is difficult to detect a detailed chemical state for samples having actual media structure using conventional x-ray photoelectron spectroscopy (XPS) since the etching process is required, because a main feature of XPS is surface sensitivity. The process which etches a cover layer has a possibility of breaking sample chemical state. The HX-PES has a larger probing depth than conventional laboratory XPS contrarily, thus it can detect the signal from the interface between films covered with other materials of samples having actual media structure on the PC substrate without an etching process. The energy of the hard x-ray for excitation was 8 keV and its incidence angle on the sample surface was 10 degrees. Photoelectrons were detected by R-4000 (Gamma-data Scienta) electron analyzer with the take-off-angle of 80 degrees. Samples having actual film structure like the L1, for HX-PES were prepared (i) with interface layers on both sides of the recording material and (ii) without an interface layer for comparison. These two samples are designed with almost the same reflectivity. The cross-sectional view of the sample is shown in Fig. 5. The structures are as the following:

ZnS-SiO_2 / Interface layer (IF) / GeBiTe/ Interface layer (IF) / ZnS-SiO_2 / Ag alloy / PC Sub. (i),

ZnS-SiO_2 / GeBiTe / ZnS-SiO_2 / Ag alloy / PC Sub. (ii).

We used the GBT film thickness 5 nm which is similar as in an actual media for HX-PES analysis. The interface layer we used is oxide based compounds with high crystallization acceleration function. Neither Ge, Te nor Bi are included in interface layers both HX-PES and XAFS. Along with a sample having an as-deposited amorphous recording film (Amo.), a sample with crystalline recording film (Cry.) was prepared. The recording film was crystallized using the same initialization equipment as is used for the initialization of rewritable HD DVDs. We made a peak survey for a wide binding energy range for the qualitative analysis before a detailed examination of each element and the electron density of states (DOS) for the valence band of the phase change recording material.

In the XAFS study, the fluorescence method was used since the object to analyze was a thin film. The incident angle of the x-ray to the sample was 30 degrees. A 7-element silicon drift detector (SDD : KETEK) was used as the x-ray detector. Distance between the sample and the SDD was set to 15 mm. The samples are analyzed without any prior processing, even without peeling off the PC substrates for XAFS. The absorption edge of Ge K-shell was used for the local structure analysis as the probe, because Ge is expected to be more dynamic than Bi and Te during the phase-change process 12). The filter of Ga_2O_3 having 6-um thickness was used between the sample and the SDD to get rid of scattered x-rays in order to use the band width of the SDD effectively. The actual media, semi-transparent L0, is used for XAFS as samples. Thickness of the recording layer is less than 10 nm. Samples were prepared (I) with interface layers on both sides of the recording material and (II) without an interface layer for comparison similar to HX-PES experiments. These two samples have almost same reflectivity. It should be noted that the L0 structure has the thinnest recording film and thus the analysis of the L1 and the single layer type media may be easier than that of the L0. The recording film we adopted is also the GBT alloy that can be applied for high-speed rewritable HD DVD media. Along with (a) Amo., and (b) Cry. samples, (c) a sample is used, on which amorphous marks (Mark trains) were recorded by using a disc tester DDU-1000 (Pulstec Industrial Co., LTD) with a 405 nm laser wavelength and 0.65 lens NA.

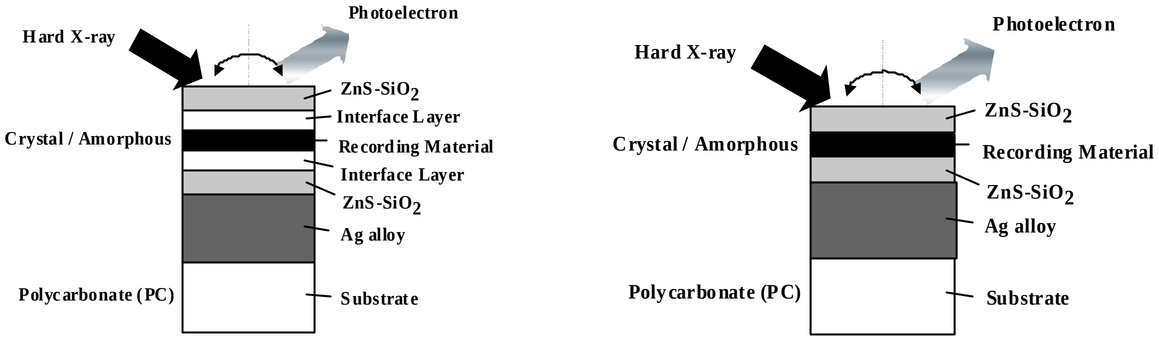
Table III. Analysis equipment and conditions for HX-PES.

The source of excitation X-ray	SPring-8 BL47XU
Excitation energy h?	7936.68 eV a)
Electron analyzer	R-4000 (Gamma-data Scienta) Pass energy: 200 eV, Slit: curved 0.5 mm, Lens mode : Transmission, ⊿E∼0.3 eV b)
The incidence angle of excitation X-ray	10 degrees
Detection angle (take-off angle : TOA)	80 degrees

a) Calibration using Au $4f_{7/2}$ peak. b) Estimation of Fermi edge profile of Au plate.

Table IV. Analysis equipments and conditions for XAFS.

The source of excitation x-ray	SPring-8 BL-16B2, “SUNBEAM”
Beam shape and area	4 mm x 4 mm
The incident angle	30 degrees
Distance between a sample and detectors	15 mm
The x-ray detector	Silicon drift detector (SDD) with 7 elements
The filter for scattered x-rays	6 um-thick Ga_2O_3



(i) With interface layers (ii) Without an interface layer (IF)

Fig. 5 Cross-sectional view of the sample for HX-PES.

4. RESULTS AND DISCUSSION

4.1. RECORDING CHARACTERISTICS OF THE 40GB DUAL LAYER MEDIA 13)

We made a dual-layer disc for experiments and evaluated it. Table V shows the recording characteristics and optical properties of L0 and L1 of made dual-layer media, respectively. The enough recording characteristics of the SbER of less than 5×10^{-5} and the PRSNR of over 15 were successfully obtained for both land and groove of both L0 and L1. Our developed dual-layer media had sufficient reflectivity of over 4 % at crystalline state of both layers. The optimum write powers were under 13 mW though no high NA lens was used in the system. This result shows that the dual-layer disc has higher sensitivity. The enough power margins of about ± 10 % were obtained. The media shows both tangential and radial tilt margins of over ± 0.5 deg. for both land and groove of both L0 and L1. The tilt angle (α) is defined as the angle between incident and reflected lights on the disc as shown in Fig. 6. These margins are similar to 36 GB dual-layer disc 2). We believe that our developed dual-layer media is feasible for practical use.

Table V Recording characteristics and Optical properties of the dual layer disc.

Layer	Land		Groove	
	SbER	PRSNR	SbER	PRSNR
L0	1.5×10^{-5}	18.5	1.5×10^{-5}	19.3
L1	1.1×10^{-6}	20.9	1.1×10^{-6}	19.1

State/Layer	Optical constants [%]		
	L0		L1
	Rc	Transmittance	Rc*
Crystalline state	5.9	49.4	5.4
Amorphous state	1.4	51.2	1.2

* These values were calculated using the transmittance of L0 and the reflectivity of L1.

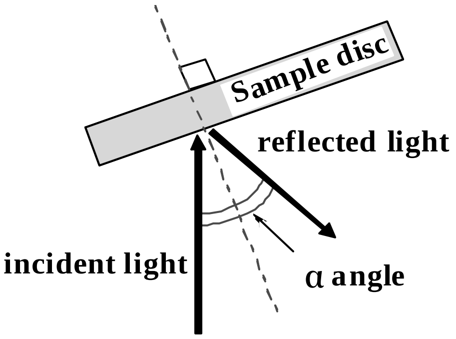


Fig. 6. Definition of tilt angle in this study.

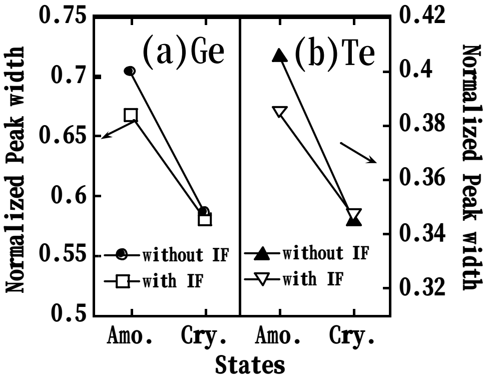
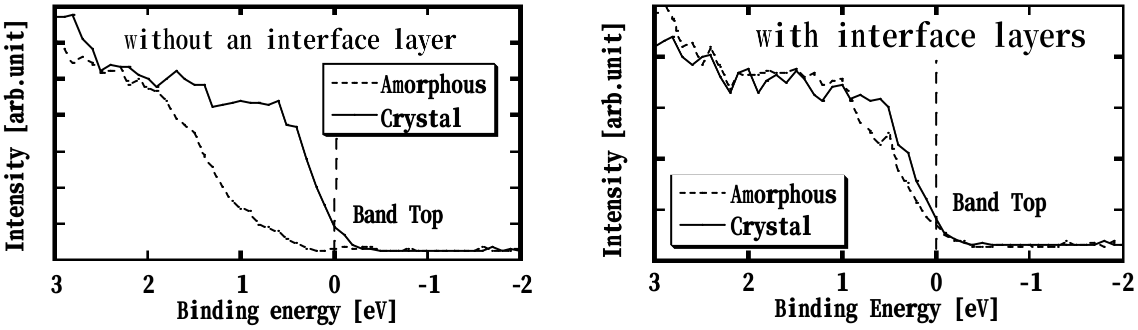


Fig. 7 Crystal-state dependence of Ge and Te peak widths.

4.2. EFFECT OF INTERFACE LAYER TO HIGH-SPEED PHASE-CHANGE RECORDING MATERIAL

Qualitative analysis results of HX-PES method for all samples showed that elements of the recording film, i.e., Ge, Bi and Te, beneath a ZnS-SiO_2 film were detectable in the sample near actual media structure nondestructively. Thus, we can analyze the detailed chemical and electronic states of the recording film using the sample near actual media structure using HX-PES method. No chemical-shift was detected. Figure 7 shows peak widths of Ge $2p_{3/2}$ and Te $3d_{5/2}$ for the Cry. and Amo. for GBT films with and without interface layers. These elements were chosen because GeTe rich composition was used. The Background signal was removed using the Shirley method 14). The Voigt function was used as the fitting function and peak widths were estimated. The peak width of photoelectron spectrum shows the binding state of each element of the sample. The peak widths of Amo. both with and without interface layers are broader than that of corresponding Cry. The peak width of Amo. with interface layers is narrower than that of Amo. without interface layers. On the other hand, the peak widths for Cry. film do not differ from each other regardless of whether the sample is with or without the interface layers. These results imply that the binding state of elements for Amo. recording film with interface layers is closer to Cry. than the Amo. films without interface layers.

Figure 8 shows the DOS for the valence band of GBT films of samples both with and without interface layers. The DOS for the Amo. without an interface layer is smaller than that of the Cry. The band-edge energy of the Amo. without an interface layer is lower by about 0.5 eV than that of the Cry. This leads to lower carrier density for electrical conduction of the Amo. than that of the Cry. and thus the higher electrical resistivity, which is consistent with our experience. On the other hand, the DOS for the valence band and the band-edge energy of the Amo. of GBT with interface layers were almost same as that of the Cry., respectively. This result may lead to almost the same carrier density for electrical conduction for the Cry. as the Amo. It should be noted that ZnS, SiO_2 and oxide interface layer materials are known as the electrical insulator and have the wide band gap, over 3 eV. On the other hand, the phase-change recording material used for the rewritable optical disc is known as the semiconductor with narrow band gap or semi-metal like material. The band top energies for the valence band of insulator materials are deeper than that of GBT and the excited conduction carrier from several insulators should be negligibly small. Therefore, these valence bands do not overlap in that of GBT. The change of DOS caused by the presence of the interface layers leading to similar DOS for both Amo. and Cry. is totally unexpected thus very interesting because the atomic arrangements should differ from each other. We speculate that these effects are a factor for the high-speed crystallization.



(a) Without an interface layer (b) With interface layers

Fig. 8 Density of states (DOS) for the valence band of the phase-change recording film (GBT).

The XAFS signal and EXAFS (Extended X-ray Absorption Fine Structure) oscillation from the actual media nondestructively were obtained successfully for all states (*i.e.* (a) Amo., (b) Cry. and (c) Mark trains) of recording film both with and without an interface layer. We analyzed EXAFS to clarify the local structure of atomic arrangement in the GBT in more detail, especially about the influence of the interface layer. The magnitude of the Fourier transforms (TF) of the $k^3 \chi(k)$ spectra of Amo. with and without interface layer are shown in Fig. 9. The k dependence of the phase shift and back-scattering amplitudes are ignored in this Fourier transformation. Therefore each peak in Fig. 9 shows little shorter distance than real interatomic distance. The peaks around 2 – 3 Å are related to the nearest-neighbor atoms around Ge. The interatomic distance, the coordination number, etc. are determined by least-squares fitting on the inverse-Fourier transformed spectra of the peaks in Fig. 9 with a correction for effect of the phase shift and the back-scattering based on the measured data. From this analysis, the peak in magnitude spectra around 2 – 3 Å of amorphous GBT with and without interface layers in Fig. 9 is assigned to the Ge and Te atoms as the nearest-neighbor of Ge atoms similar to GeTe [15]. The interface layers influence slightly the local structure of the nearest-neighbor of Ge atoms in the recording material. The atomic distance did not depend on with or without interface layers. On the other hand, the coordination number varied weakly by the existence of interface layers. These results suggest that interface layers affect slightly the coordination number of the nearest-neighbor of Ge atoms in amorphous GBT although the atomic distance is not changed.

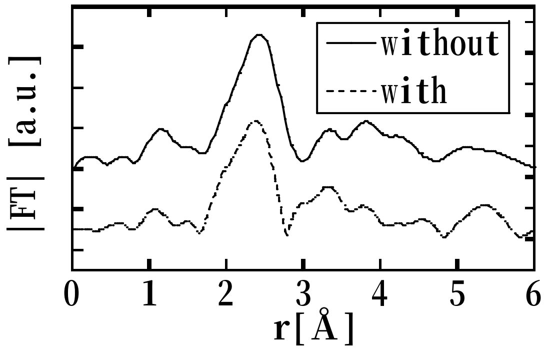


Fig. 9 FT experimental EXAFS spectra of Ge K-edge for GeBiTe.

We speculate that this slight change of the coordination number changes the electronic state of phase-change recording material. This means that the interface layer changes the electronic state of the recording layer and promotes crystallization acceleration without significantly affecting the local structure of the atomic arrangement. These findings are useful in understanding the phase-change mechanism in the optical recording media. And these can also be applied for the research of such semiconductor devices as PRAMs (Phase-change Random Access Memory).

5. CONCLUSIONS

We have developed the dual-layer rewritable HD DVD media having user data capacity of 40 GB (20 GB/layer) for the optical system with the NA of 0.65 and the wavelength of 405 nm, and light incidence on 0.6-mm-thick substrate having the land and groove format at the 1X speed operation rate. A key technology is more accurate thermal analysis technology utilizing the accurate measurement of thermo-physical properties for thin films using thermo-reflectance method. It was expected that TP can be made smaller from the viewpoint of thermal design of the media. As the result, the higher density rewritable media was developed. Additionally, it is important to understand the high speed phase-change recording mechanism for the development of the high-speed rewritable media as a vital foundation. The interaction between high-speed phase-change recording material and interface layer is analyzed by using the synchrotron orbital radiation, in particular, XAFS and HX-PES method. The interface layer changes the electronic state of the recording layer, particularly DOS, and promotes crystallization acceleration with only slightly affecting the local structure of the atomic arrangement according to these analyses. We speculate that this effect is an important factor for the high-speed crystallization. These findings are useful in understanding the high-speed phase-change mechanism in the optical recording media and the semiconductor device. The dual-layer rewritable HD DVD media with larger capacity has been achieved and even higher speed operation rate will be realized based on these technologies, in addition to our material technologies.

ACKNOWLEDGEMENT

The synchrotron radiation experiments were performed at SPring-8 with the approval of Japan Synchrotron Radiation Research Institute (JASRI) as Nanotechnology Support Project of the Ministry of Education, Culture, Sports, Science and Technology. (Proposal No.2005B0232, 2006A1641, 2006B1599 / BL-No.47XU)

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