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Study of Al–Ti/Si bi-layer as the recording media for write-once HD-DVD optical disks

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ABSTRACT

Optimum structure for HD-DVD optical disks containing Al–Ti/Si bi-layer recording system was identified by reflectivity simulation and dynamic test of disk samples. For the disk sample with optimized structure, the maximum partial response signal-to-noise ratio (PRSNR) of 19.1 dB, minimum simulated bit error rate (sbER) of 1.7×10^{-7} and modulation >0.6 were achieved at the writing power (P_w) = 11.2 mW. Transmission electron microscopy (TEM) revealed that the polycrystalline granular clusters constitute the recording marks. Subsequent analyses evidenced that element mixing/alloy reactions occur in between Si and Al–Ti layers and the formation of $Al_{3.21}Si_{0.47}$ crystalline phase is responsible for the signal recording in the disk samples.

1. Introduction

Optical disks are the most important external data storage devices for multimedia or personal data files because of their large recording capacity, interchangeability and media portability [1–3]. One of the main trends for the development of optical disks is to increase the recording capacity as it can be seen from the evolution of compact disk (CD) [4] into digital versatile disks (DVDs) [5–6]. At present, high-density DVD (HD-DVD) and Blu-ray (BD-R) disk are recognized as the optical recording media for next-generation and many studies relating to recording materials have been reported [7–17]. In addition to phase-change alloys and organic dye materials, single-layer alloys such as AlSi [7–9], BiGe [10,11] and bismuth iron oxide (BiFeO) [12,13], bi-layered structures such as Cu/Si [14], Cu/*a*-Si [15], ZnO/Ge [16], and Ge/Au [17] have been proposed for the write-once type optical recording. Their recording mechanisms are generally resulted from the thermally activated element mixing and/or alloy reactions when the recording stack is subjected to the irradiation of laser beam.

In this work, disk structure optimization, signal properties, microstructure change and recording mechanism of write-once HD-DVD disk containing Al–Ti/Si bi-layer as the recording media were investigated. The Al–Ti alloy and Si were selected since they are relatively inexpensive materials and can be easily acquired. In addition, Al and its alloys form thin, dense oxide layers to inhibit further oxidation in their interiors. Such a self-protecting feature implies a better reliability of disks containing Al alloys. Furthermore, from the production point of view, this allows an easy maintenance of vacuum deposition chambers handling Al alloys in comparison with those for the production of other disks types containing recording media such as Cu/Si. Satisfactory signal properties, PRSNR = 19.1 dB, sbER = 1.7×10^{-7} and modulation >0.6 at the optimized writing power (P_w) of 11.2 mW, were achieved in the disk samples containing Al–Ti/Si bi-layer with optimized structure. TEM characterizations revealed that polycrystalline agglomerates constitute the recording marks regime. The alloy phase type and element distribution were analyzed and the mechanisms of signal recording was discussed.

2. Experimental

2.1. Optimization of disk structure

Optimization of disk structure was carried out by, first, substituting the optical constants including refraction index (n) and absorption coefficient (k) for each layer of optical disk into Spectrum Simulation, a self-developed software, to identify the preliminary disk structures that possess reflectivities in the range of 16–32% as required by HD-DVD Specifications [18]. Table 1 lists the optical constants adopted for the simulation. According to the preliminary simulation result, thickness ranges for each of layers were then designated and various disk samples were constructed by DOE (Design of Experiment) method as depicted in Table 2. Accordingly, the disk samples were fabricated *via* sputtering process and their reflectivities and PRSNR were measured by the dynamic test. The measured results are shown in Table 2 and they were subsequently substituted into Minitab Release 14 Statistical Software to identify the primary affect factor on the disk signal properties. After determining the layer type that affects most on the signal properties, the disk layer structure was

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Table 1
Optical constants for disk structure simulation

Layer type	Optical constants (for λ = 405 nm)	
	n	*k*
ZnO–SiO_2	2.14	0.01
Si	4.18	0.72
Al–Ti	0.41	3.80
Ag	0.23	2.40
PC	1.62	0.00

fine-tuned accordingly, and in association with the reflectivity and PRSNR measurements, in order to identify the optimum disk structure.

2.2. Disk sample preparation

Optical disk samples were prepared according to the HD-DVD Specifications [18] by using a self-designed six-target sputtering system at a background pressure better than 10^{-6} torr. The five-layered disk structure was constituted by pre-grooved PC substrate (0.6 mm), lower ZnS–SiO_2 dielectric layer, Si/Al–Ti bi-recording layer, upper ZnS–SiO_2 dielectric layer and Ag reflection layer with cross-sectional structure depicted in Fig. 1. After the deposition of Ag layer, another 0.6-mm PC substrate was attached on to complete the preparation of optical disk samples.

2.3. Dynamic test

A dynamic tester (ODU-1000, Pulstec Industrial) equipped with a 405-nm laser diode and a numerical aperture (NA) of 0.65 was adopted to characterize the signal properties of optical disk samples. The characterization was performed at clock frequency = 64.8 MHz, linear speed = 6.61 m s^{-1} and the track pitch = 0.4 μm.

2.4. Microstructure

The microstructures and phase identification of the recording marks were examined by a transmission electron microscope (TEM, JEOL FX-II 2010) equipped with an energy dispersive spectrometer (EDS, Link ISIS 300). During the examination, selected area electron diffraction (SAED) was also performed in order to identify the crystallinity of phases. The plan-view TEM (PTEM) samples were prepared in accordance with the method reported by Chen et al. [19]. The disk sample was first cut into small pieces by using scissors. After dissolving the PC substrate in CH_2Cl_2 solution, the specimen was mounted on a copper (Cu) mesh and transferred to the TEM for microstructure characterization. The cross-sectional TEM (XTEM) samples were also prepared by using an ultramicrotomy (Leica Reichert Ultracut S) so as to identify the layer thickness of optical samples.

3. Results and discussion

3.1. Optimization of disk structure

Table 2 lists the disk samples constructed by DOE method and the signal properties measured by the dynamic test. It is noted that these are the preliminary values measured prior to the fine tune of disk layer structure and they simply serve as the guideline for the identification of optimum disk structure described as follows.

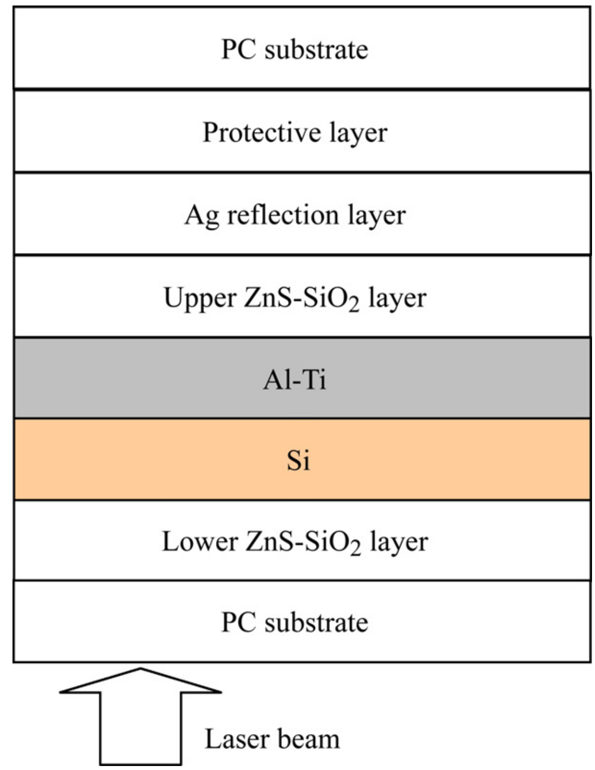

Fig. 1. Cross-sectional structure of optical disk samples.

An analysis of signal properties shown in Table 2 indicates that thickness increment of lower/upper ZnS–SiO_2 dielectric layer and Al–Ti recording layer by 1 nm causes 0.5% decrease of reflectivity and thickness increment of Si recording layer by 1 nm causes 0.4% decrease of reflectivity. Table 2 also shows that the PRSNR increases with the increase of reflectivity that the PRSNR becomes higher than 2.5 dB when reflectivity exceeds 4%. Fig. 2(a)–(e) depict reflectivities and PRSNR's of the disk samples as a function of thickness. Among them, the steepest slopes occur in the plot for Al–Ti layer (see Fig. 2(c)). Since it possesses higher thermal conductivity and lower melting point than that of Si, the Al–Ti layer is thus the key element to ignite the alloy reaction with Si to form the recording marks when the laser beam irradiates on the bi-layer structure.

Table 2
The disk samples constructed by DOE method and the measured reflectivities and PRSNR by the dynamic test

Sample designation	Thickness (nm)					Reflectivity (%)	PRSNR (dB)	Sensitivity (mW)
	Lower ZnS–SiO_2	Si	Al–Ti	Upper ZnS–SiO_2	Ag			
1	30	12	9	10	100	3.99	<1	11
2	35	12	9	10	80	3.59	<1	11
3	30	16	9	10	80	4.96	2.5	11
4	35	16	9	10	100	1.84	<1	11
5	30	12	14	10	80	1.37	<1	11
6	35	12	14	10	100	2.13	<1	11
7	30	16	14	10	100	1.63	<1	11
8	35	16	14	10	80	< 1	<1	11
9	30	12	9	15	80	6.62	18.5	11
10	35	12	9	15	100	4.3	2.5	11
11	30	16	9	15	100	5.20	3	11
12	35	16	9	15	80	4	2.5	11
13	30	12	14	15	100	1.49	<1	11
14	35	12	14	15	80	1.35	<1	11
15	30	16	14	15	80	2.67	<1	11
16	35	16	14	15	100	1.51	<1	11

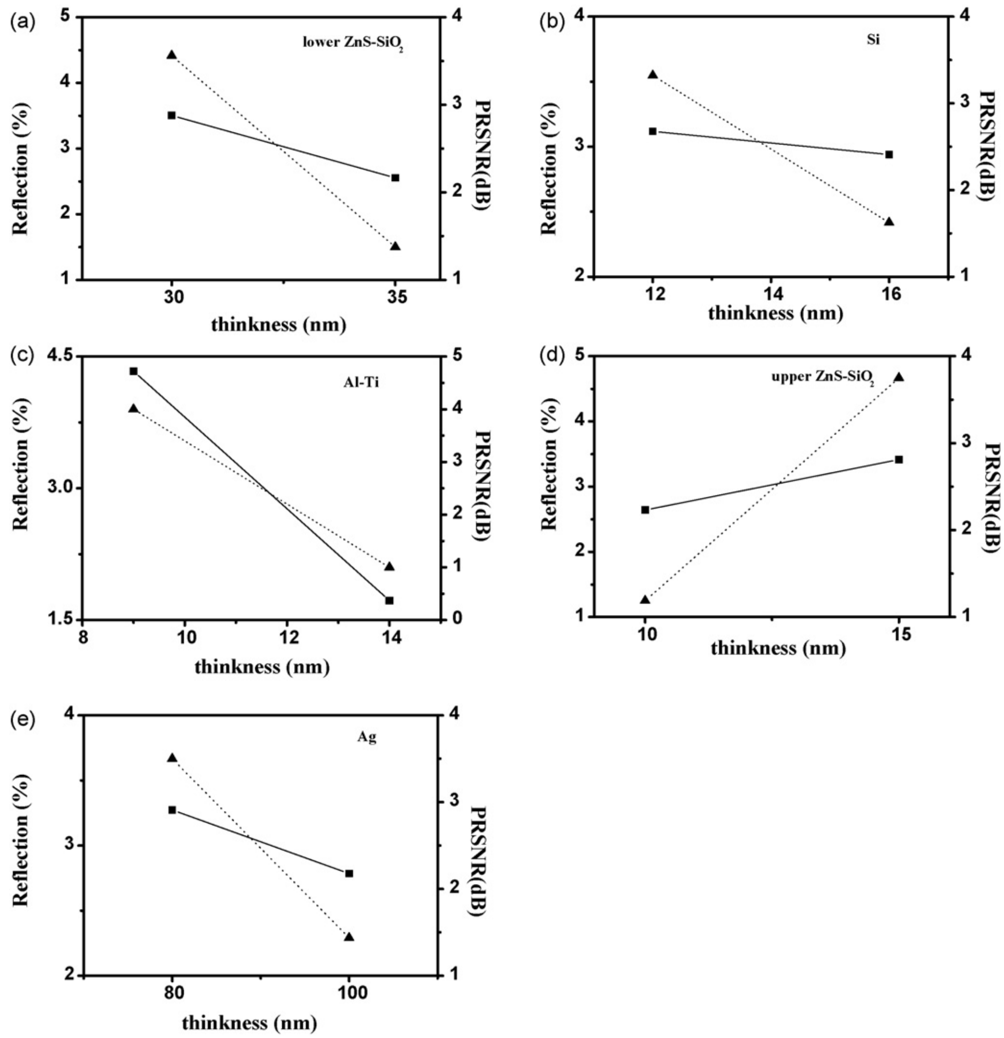

Fig. 2. The reflection of disk sample as a function of thickness of (a) lower ZnO–SiO_2 layer, (b) Si recording layer, (c) Al–Ti recording layer, (d) upper ZnO–SiO_2 layer and (e) Ag reflection layer calculated by Minitab software.

Hence, the thickness of Al–Ti layer is the primary affect factor for the structure of HD-DVD disk samples as illustrated by Fig. 2(c).

The iteration of sample preparation by fine tuning the Al–Ti layer thickness of optical disk sample to achieve the highest reflectivity (*i.e.*, sample 9 in Table 2), and with the aid of reflectivity measurement and XTEM observation, eventually led to the optimum optical disk structure as: PC substrate/ZnS–SiO_2(35 nm)/Si(9 nm)/Al–Ti(9 nm)/ZnS–SiO_2(15 nm)/Ag(90 nm)/PC substrate. Fig. 3 shows the XTEM image of the optimized optical disk structure. Subsequent signal characterizations and microstructure observations were carried out based the disk samples with such an optimized structure.

3.2. Signal properties

Fig. 4 presents the variation of PRSNR and sbER with the writing power (P_W) of disk samples obtained by dynamic test. According to the HD-DVD Specifications [18], the PRSNR must be higher than 15 dB and the sbER must be lower than 10^{-5}. As seen in Fig. 4, the optical disk prepared in this work achieved the maximum PRSNR of 19.1 dB and the minimum sbER of 1.7×10^{-7} at the optimized P_W of 11.2 mW. Further, the modulation of optimized disk sample was found to be greater than 0.6. As stated previously, various materials have been proposed for write-once optical recording in

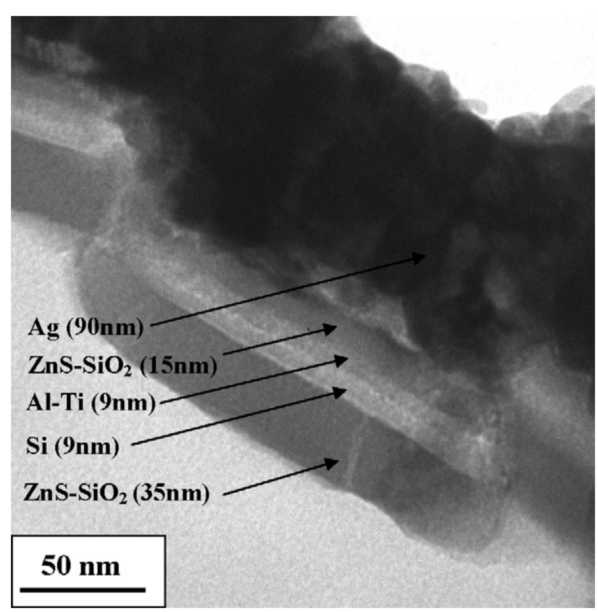

Fig. 3. XTEM micrograph of the optimized disk sample.

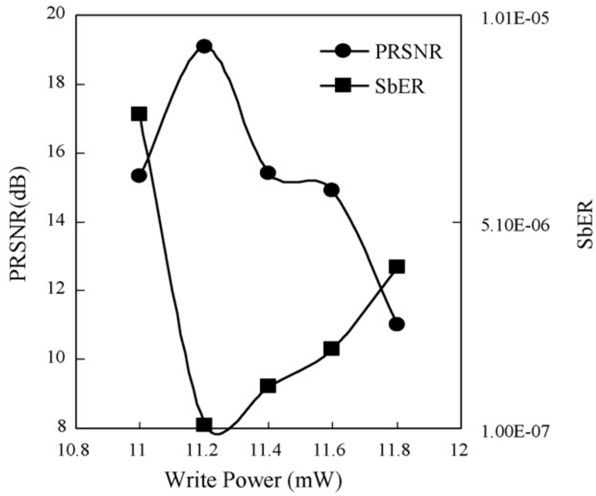

Fig. 4. Variation of PRSNR and sbER of disk samples versus the writing power (P_w).

blue-laser era [7–17]. For single-layer AlSi alloy applied to HD-DVD, PRSNR ≈ 18.5 dB, sbER ≈ 2×10^{-5}, jitter value <7% and the modulation >0.4 were reported [7–9]. The HD-DVD disk containing Ge/Au bi-layer achieved PRSNR = 16 dB and the sbER = 9.9×10^{-7} at 1× recording speed [17]. The results presented above show that the Al–Ti/Si bi-layer disk samples possess a better disk signal properties in comparison with those reported by previous studies. As revealed by the TEM analysis presented in next section, the Al–Ti/Si bi-layer produced by sequential sputtering deposition is amorphous and such a uniform background is beneficial to the signal contrast when marks are written in the disk samples. Compared with the disks containing single-layer AlSi alloy, it is speculated that the as-deposited recording layer, if it were prepared by using a hyper-eutectic AlSi alloy target [9], is likely to be a mixture of Al–12.6 wt.% Si eutectic phase and solid solution Si according to the Al–Si binary phase diagram [20]. The two alternative phases might result in some structural inhomogeneity. This raises the background noise and hence the inferior signal properties of optical disks in comparison with those achieved in this study [7–9].

Eye pattern corresponding to the signals ranging from 2 T to 11 T read directly from oscilloscope is shown in Fig. 5. Though the pattern looks somewhat blurry, it illustrates that the random signals could be satisfactorily written in the disk samples containing the Al–Ti/Si bi-layer structure. We note that this work is a preliminary study on the feasibility of Al–Ti/Si bi-layer as the write-once recording medium and it was carried out by adopting the PC substrate and writing strategy available at hand without further optimizations. This leads to some seemingly low signal values, for instance, the "highest" reflectivity listed in Table 2 is only 6.62% which might result from the deep land-and-groove geometry of PC substrate adopted for disk sample preparation. It is believed that the better signal properties and sharp eye patterns could be accomplished if the writing strategy and PC substrate geometry were subsequently adjusted.

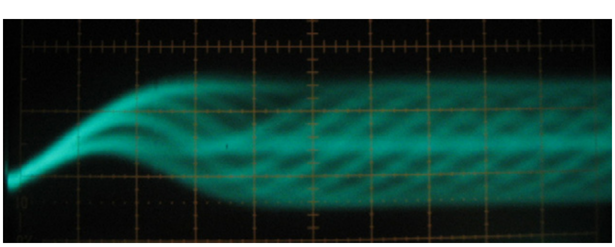

Fig. 5. Eye patterns for random signals read directly from oscilloscope.

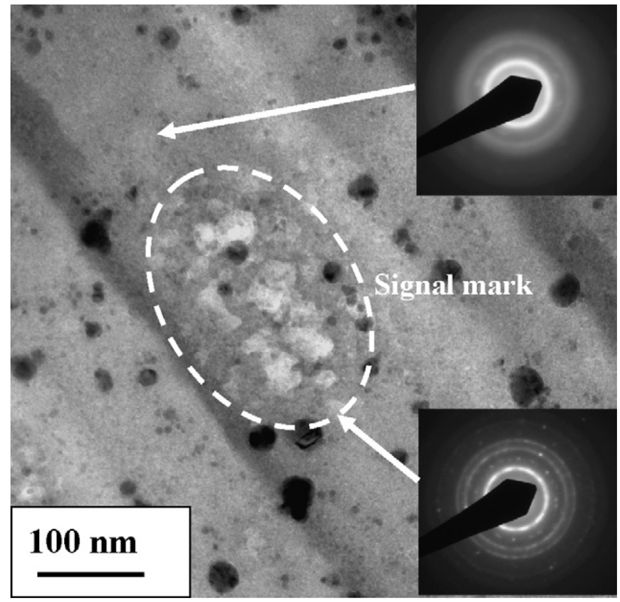

Fig. 6. PTEM image of a recording mark in optical disk sample. The SAED patterns attached at upper and lower right-hand corners were taken from the areas outside and right on the mark, respectively.

3.3. Microstructure

Fig. 6 shows the PTEM image of signal marks in a recorded disk sample. The inserted SAED pattern at the upper right-hand corner is taken form the area outside of the mark while the pattern at the lower right-hand corner corresponds to the signal mark regime. TEM characterization shown in Fig. 6 clearly reveals that the polycrystalline agglomerate with grain sizes about 30–40 nm embedded in amorphous matrix constitutes the signal mark. We calculated the *d*-spacing corresponding to the each of the diffraction rings in SAED pattern of polycrystalline agglomerate, and with the aid of Joint Committee of Powder Diffraction Standard (JCPDS file card No. 41-1222), to identify the alloy phase in the signal marks as $Al_{3.21}Si_{0.47}$. Apparently, the alloy reaction of Al with Si induced by laser irradiation in the bi-layer structure generated such a polycrystalline phase and was responsible for the signal recording in our disk samples.

Fig. 7 shows the variation of composition in the signal mark. The composition analysis was carried out along a line across the middle of mark regime by using the EDS attached to TEM. At the edges of mark (*i.e.*, positions 1 and 5), distinct signal intensities of Si and Al were observed. This should result from the bi-layer recording structure that the upper layer of TEM sample (in this case Si should be the upper layer) produces more X-ray signal when detecting electrons reach the sample. The EDS signals of Al and Si gradually merge together in the middle of mark, indicating the occurrence of element mixing of Al and Si. This also confirms the alloy reactions and formation of crystalline phase described above. As shown in Fig. 7, the EDS analysis also revealed a rather smooth signal variation of Ti element across the signal mark. In this work, the Al–1.5 wt.%Ti sputtering target was adopted for disk sample preparation. The comparatively small Ti content implies an insignificant concentration change of Ti around the signal marks. Thus, Ti element plays a negligible role on the signal properties of disk samples and phase constitution of signal marks.

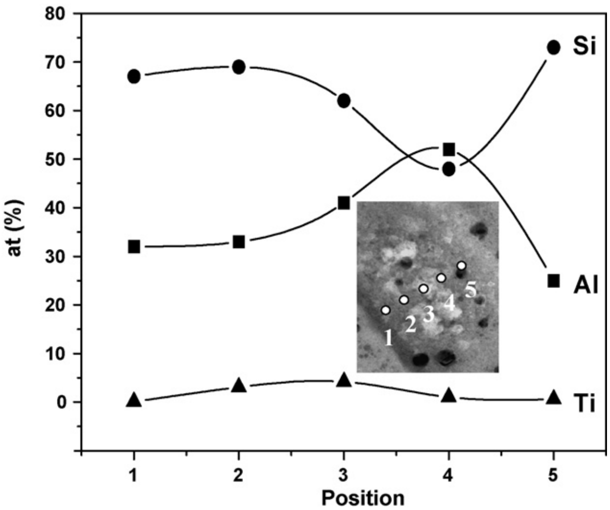

Fig. 7. EDS analysis of composition variation of the recording mark shown in Fig. 6.

4. Conclusions

The disk structure optimization and recording mechanism of write-once HD-DVD disk containing Al–Ti/Si bi-layer recording system were investigated in this work. Simulation study indicated that the thickness of Al–Ti recording layer is the primary factor affecting the optical reflectivities of disk samples. For the disk sample with optimized structure deduced by simulation study and preliminary signal property measurement, PRSNR = 19.1 dB, sbER = 1.7×10^{-7} and modulation >0.6 were achieved at P_w = 11.2 mW as revealed by dynamic test. The TEM characterization revealed the formation of polycrystalline recording mark in the disk samples. Phase identification and EDS composition analysis evidenced that element mixing/alloy reactions occurs in between Si and Al–Ti layers and formation of $Al_{3.21}Si_{0.47}$ crystalline phase is responsible for the signal recording of disk samples.

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References

[1] M. Takenaga, N. Yamada, K. Nishiuchi, N. Akahira, T. Ohta, S. Nakamura, T. Yamashita, J. Appl. Phys. 54 (1983) 5376.
[2] Y. Unno, K. Goto, Proc. SPIE 382 (1983) 32.
[3] M. Terao, S. Horigome, K. Shigematsu, Y. Miyauchi, M. Nakazawa, J. Appl. Phys. 62 (1987) 1029.
[4] B. Tieke, G.R. Langereis, E.R. Meinders, J.G.F. Kablau, R. Woudenberg, R.A.J. van Kollenburg, Jpn. J. Appl. Phys. 41 (2002) 1735.
[5] K.S. Min, Y.J. Huh, H.K. Shim, Jpn. J. Appl. Phys. 38 (1999) 1675.
[6] K. Nishiuchi, H. Kitaura, N. Yamada, N. Akahira, Jpn. J. Appl. Phys. 37 (4B) (1998) 2163.
[7] B.M. Chen, R.L. Yeh, Proc. SPIE 5380 (2004) 141.
[8] B.M. Chen, H.F. Chen, R.L. Yeh, J.M. Chung, Jpn. J. Appl. Phys. 43 (7B) (2004) 5018.
[9] B.M. Chen, J.H. Chen, L.C. Chung, Patent No. 220523, Taiwan, ROC, August (2004).
[10] Y. Hosoda, T. Izumi, A. Mitsumori, F. Yokogawa, S. Jinno, H. Kudo, Jpn. J. Appl. Phys. 42 (2003) 1040.
[11] Y. Hosoda, A. Mitsumori, M. Sato, M. Yamaguchi, Jpn. J. Appl. Phys. 43 (2004) 4997.
[12] N. Sasa, Y. Hayashi, T. Fujii, K. Otaka, A. Watada, H. Kamezaki, H. Komoda, Jpn. J. Appl. Phys. 43 (2004) 4972.
[13] N. Sasa, Y. Hayashi, T. Fujii, A. Watada, H. Komoda, Jpn. J. Appl. Phys. 44 (2005) 3643.
[14] A.E.T. Kuiper, R.J.M. Vullers, D. Pasquariello, E.P. Naburgh, Appl. Phys. Lett. 86 (2005) 221921.
[15] Y.C. Her, C.L. Wu, Jpn. J. Appl. Phys. 43 (2006) 1013.
[16] C.P. Liu, Y.T. Hung, J.S. Tsai, G.J. Huang, T.R. Jeng, Jpn. J. Appl. Phys. 46 (2007) 7365.
[17] T.H. Wu, P.C. Kuo, Y.H. Fang, J.P. Chen, P.F. Yen, T.R. Jeng, C.Y. Wu, D.R. Huang, Appl. Phys. Lett. 90 (2007) 151111.
[18] DVD Specifications for High-Density Recordable Disc (HD DVD-R) for Blue Laser Optical System, Version 0.9, The DVD Forum, July, 2004.
[19] H.W. Chen, T.E. Hsieh, J.R. Liu, H.P.D. Shieh, Jpn. J. Appl. Phys. 38 (1999) 1691.
[20] Thaddeus B. Massalski (editor-in-chief), Binary Alloy Phase Diagrams, 2nd ed., ASM International, Materials Park, Ohio, 1990.