Anneal-less Domain Wall Displacement Detection of 15 Gbit/in^2 land-groove recording using a deep groove substrate and a red laser

Tetsuhiro Sakamoto*, Yasuhito Tanaka, Shingo Imanishi, Motohiro Furuki,
Nobuyuki Arakawa and Kazuhiko Fujiie ** [a]
Optical System Development Group, Broadband Network Company, Sony Corporation
6-7-35 Kitashinagawa, Shinagawa-ku, Tokyo, Japan 141-0001;
[a]Networked CE Laboratories, Sony Corporation
Shinagawa Tec. 2-15-3 Konan, Minato-ku, Tokyo, Japan 108-6201,

ABSTRACT

Domain Wall Displacement Detection (DWDD) medium with no annealing method, which we call "anneal-less" DWDD medium, has been improved for practical use. The key technologies of our progress are not only an optimum design of the magnetic film structure but also a deep groove substrate for land-groove recording with a quite unique groove form. The substrate was prepared by using the mastering process with a reactive ion etching (RIE) method. We achieved 15 Gbit/in^2-areal density with wide system tolerances using the anneal-less DWDD medium, a 660nm-laser and a 0.60 NA objective lens. The areal density corresponds to 4.7 GB-capacity on a disc like MiniDisc^{TM} (MD) with a 64 mm-diameter.

Keywords: domain wall displacement detection, DWDD, land-groove recording, deep groove, reactive ion etching, RIE, MiniDisc, red laser, DVD, 4.7GB

1. INTRODUCTION

DWDD[1] has the most potential to realize high linear density without using a blue laser or a lens of a high numerical aperture (NA). It offers the possibility to enhance the existing format of magneto-optical (MO) disc while keeping the conventional optical parameters unchanged. The authors previously reported the DWDD MO medium applied to MD system[2]. Land-groove recording was used in the system with a 660 nm-laser and a lens of 0.52 NA. The DWDD MO medium required no annealing process for good signal properties. We call this type of DWDD medium an "anneal-less" DWDD medium. Wide laser power margins were obtained at 7.2 Gbit/ in^2 equivalent to 2.3 GB capacity per side in MD size using a land-groove substrate with a deep groove.

Koyama et al. proposed an excellent optical disc system of 3.0 GB per side in 2 inch-diameter disc with groove recording[3]. The capacity corresponds to an areal density of 15 Gbit/in^2 while achieving a linear density of 80 nm/bit. They used special techniques to shorten the track pitch and the bit length, which were a sampled servo method for tracking and a land-annealing method. However, they are not easy to use especially in mass production.

In this study, we tried to achieve an areal density of 15 Gbit/in^2 using an anneal-less DWDD medium. Optical parameters are almost the same as those of the Digital Versatile Disc (DVD) system, the wavelength of laser diode is 660 nm and the NA of the objective lens is 0.60. Land-groove recording was applied to shorten the track pitch and to allow easy tracking. The groove depth was around $3\lambda / 8n$ (λ: wavelength of laser, n: refractive index of substrate) with a unique groove form prepared by using a reactive ion etching (RIE) technique[4]. The RIE substrate is very effective for a short bit length and wide laser power margins. The magnetic property design of MO films is also improved. In this paper, we report various tolerances at 15 Gbit/in^2 equivalent to 4.7 GB-capacity per side in MD size.

2. EXPERIMENTS

2.1 RIE substrate

In order to achieve 15 Gbit/in^2 with an anneal-less DWDD, we prepared a special substrate for land-groove recording that had a unique groove form as shown in Fig.1 (a) and (b). The top view and the cross-sectional view of AFM images

---

* Tetsuhiro.Sakamoto@jp.sony.com; phone 81 3 5448-2547; fax 81 3 5448-4104
** Kazuhiko.Fujiie@jp.sony.com; phone 81 3 5769-5348; fax 81 3 5769-5926

of the groove correspond to (a) and (b) in Fig. 1, respectively. Table 1 shows measurements about the groove geometry. The substrate has two angles θ1 and θ2 of inclination at each groove wall, about 50 and 75 degrees on one side as shown in Fig. 1 (b). As a result of comparison with other groove forms, we found that the groove form like that shown in Fig. 1 is suitable for an anneal-less DWDD medium to obtain system tolerances in land-groove recording. The surface roughness on land and groove was confirmed to be less than 0.35 nm and the roughness of groove wall was also confirmed to be smaller than the conventional one from the result of AFM (atomic force microscope) measurement. These two features of the substrate, a smooth surface and a deep groove with a unique form, are realized by means of the RIE technique in a mastering process. The RIE substrate is required to achieve high areal density with an anneal-less DWDD because the features are very effective for a short bit length and wide laser power margins as explained in the following.

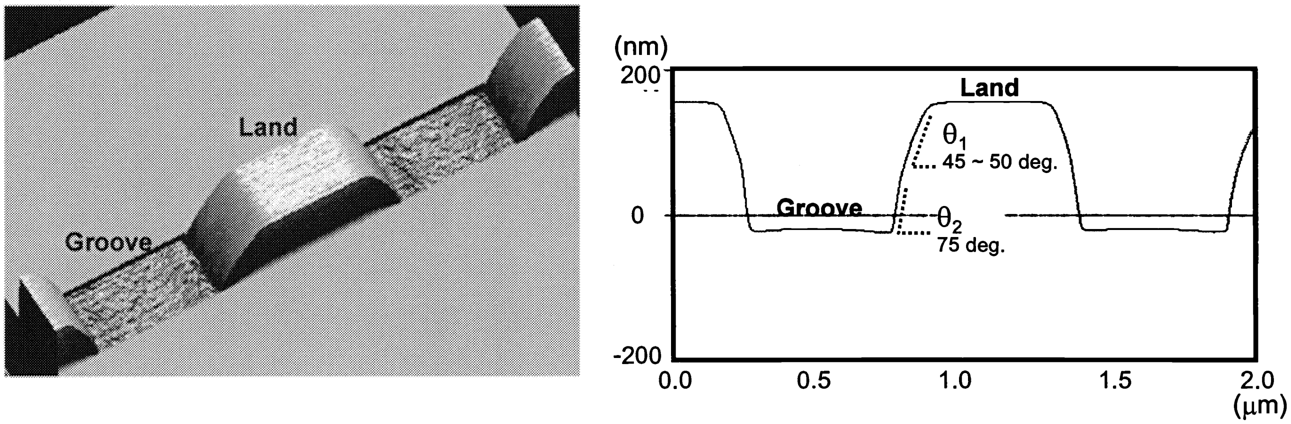

Figure 1: Substrate we used,
(a) Top view.
(b) Cross-sectional view.

depth [nm]	177.84
θ_2 [deg.]	45~50
θ_1 [deg.]	75
G-Ra [nm]	0.339
L-Ra [nm]	0.274

Table 1: Measurements of the groove geometry.

2.2 Anneal-less DWDD disc structure

Figure 2 shows a cross-sectional view photograph of TEM (transmission electron microscope) of the DWDD film on the deep groove substrate. The bottom part in the figure is a substrate and dark gray areas correspond to silicon nitride layers. The darkest area corresponds to the DWDD magnetic film and the film consists of four magnetic layers as shown in Fig. 3. Figure 3 shows the schematic structure of the anneal-less DWDD film stack. The MO films consist of a memory layer, a 1st switching layer, a 2nd switching layer and a readout layer, which are sandwiched between the dielectric SiN layers. The element composition of each layer is shown in Fig. 3.

To improve bit density, not only a smooth surface of substrate but also the magnetic property of each MO film, especially temperature characteristics, are quite important. The reason why a smooth surface allows stable domain wall motion is that some resistant force against the domain wall, a domain wall coercive force originating from roughness on the surface and an irregular wall energy originating from jaggedness at groove edges, are reduced significantly[4]. As mentioned, the magnetic property in this study, mainly two parts of the magnetic film, was modified. One part was the use of another switching layer with lower Curie temperature instead of a control layer. Another was an optimum difference of Curie temperature between the readout layer and the switching layer. The former has an effect in control of dropout during readout and the latter decreases the irregular variation of domain wall displacement that causes a bit shift or higher jitter value.

To improve track density, a film discontinuity and a good bottom coverage in groove are very important. From the result of our other experiments about film discontinuities with some kinds of groove form, we found that a film discontinuity as shown at groove edges in Fig. 2 is very effective for improvement of cross write characteristics[2]. We think that the discontinuity works as a thermal and magnetic boundary between land and groove. A good bottom coverage enables good signal properties in groove, especially in recording. It is usually difficult to obtain both effects at the same time because of the film deposition condition. In this study by using a unique groove form, however, the film discontinuity at groove edges and good bottom coverage in groove are achieved very well.

As mentioned above, the anneal-less DWDD was optimized in its magnetic film design and was supported by the RIE substrate having a deep groove with a unique form for the purpose of achieving high areal density.

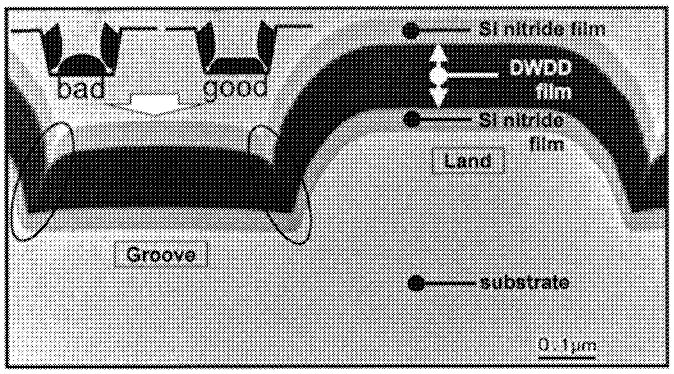

Figure 2: Cross-sectional TEM photograph of an anneal-less DWDD disc.

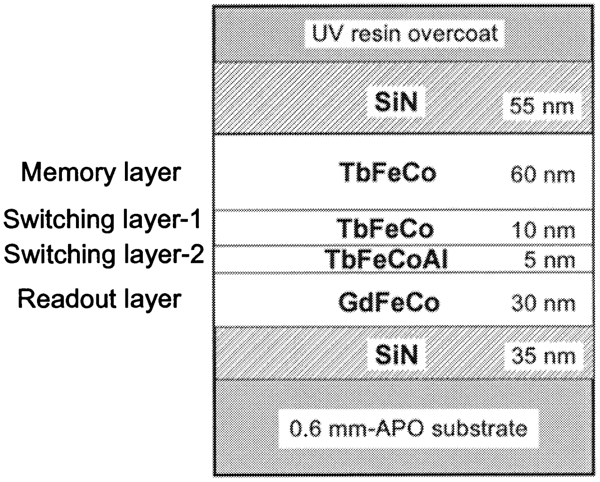

Figure 3: Schematic structure of the DWDD film stack.

2.3 Measurement conditions

Measurement conditions were set as shown in table 2. The wavelength of laser diode, NA of the objective lens and thickness of the substrate are almost the same as in the DVD system. Recording tracks were both land and groove. The groove depth was 178 nm which corresponds to around 3λ / 8n. No wave plate for optical phase compensation was used in this experiment. The track pitch was 540 nm in land-groove recording and the bit length was 80 nm; therefore, areal density was 15 Gbit/in^2. The substrate was made of amorphous polyolefin (APO) and was prepared with an injection molding from a metal stamper, which was made with the mastering process including an RIE process. There is no special reason for using the injection material of APO. The groove form was described as in the previous subsection.

A (1, 7) RLL modulation pattern was recorded by using laser-pulsed magnetic field modulation (LP-MFM) with pulse duty of 30 %. PR (1, -1) and Viterbi detection were used for measuring bit error rate. The channel clock was fixed at 18 MHz, so the linear velocity was 0.96 m/sec at the bit length of 80 nm.

Wavelength	**660 nm**	**Areal density**	**15 Gbit/in^2**
NA	**0.60**	**Recording**	**Laser-pulsed MFM**
Substrate	**0.6 mm (APO)**	**Modulation**	**(1, 7) RLL**
Groove depth	**178 nm**	**Detection**	**PR (1, -1) + Viterbi**
Track pitch	**540 nm (L/G)**	**Linear velocity**	**0.96 m/sec**
Bit length	**80 nm**	**Channel Clock**	**18 MHz**

Table 2 : Measurement conditions.

3. RESULTS AND DISCUSSION

3.1 Linear density and required magnetic field for recording

At first we evaluated the linear density characteristic and required magnetic field for recording before measuring system tolerances. Figure 4 shows linear density characteristics on land and in groove with double Y axes. The solid lines with closed markers correspond to bit error rates using the left axis and the broken lines with opened markers correspond to jitter values using the right axis as a function of a bit length. All bit error rates on land (circles) and in groove (boxes) were sufficiently smaller than 3 x 10^{-5} at bit lengths more than 80 nm. But the bit error rate in groove increases suddenly at bit lengths less than 75 nm. We believe the increase of bit error rate in groove was caused by dropout because we confirmed that errors of 2 bits or more were generated due to dropouts, even though the jitter values on both land and groove were almost the same as each other at bit lengths less than 75 nm. Therefore the bit length was set to 80 nm at which system tolerances were measured.

Figure 5 shows the bit error rate dependence on the recording magnetic field on land and in groove. The recording field was set at +/- 27.5 kA/m from the result in Fig. 5. The required magnetic field is not small yet but will be small in near future study.

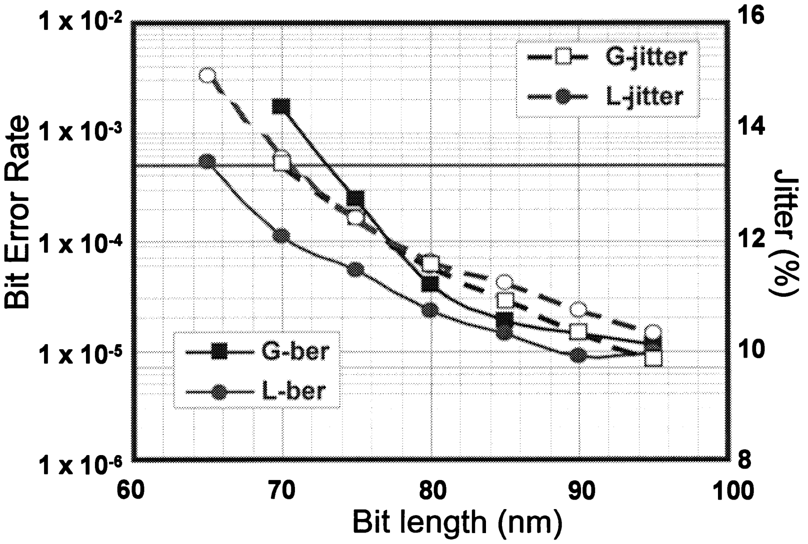

Figure 4: Linear density characteristic.

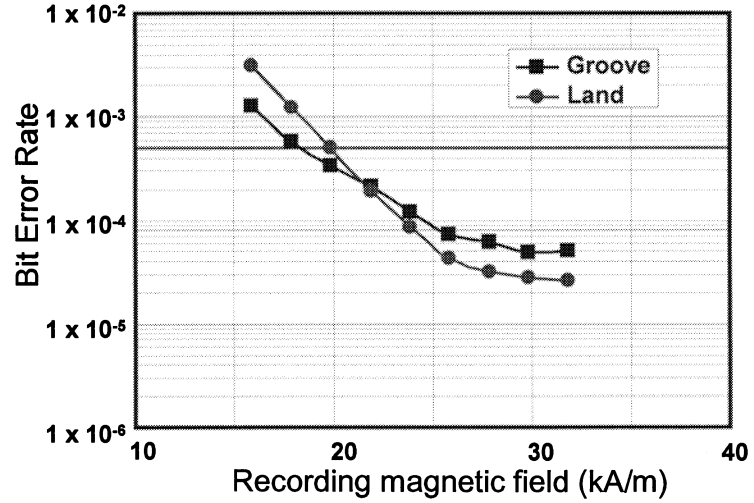

Figure 5: Required recording magnetic field.

3.2 System tolerances at 15 Gbit/in^2

Figure 6 shows laser power tolerances on land and in groove during readout with cross-talk from adjacent tracks. The upper limits of the margin are decided by data erasure, so the magnetic property of the memory layer should be improved at high temperature. When the criterion of bit error rate is set at 5 x 10^{-4}, the readout power tolerances are 1.51 mW +/- 13.3 % on land and 1.33 mW +/- 15.8 % in groove.

Figure 7 also shows laser power tolerances in recording. Solid lines with closed markers correspond to overwrite characteristics with cross-talk on land and in groove. Broken lines with open markers correspond to crosswrite characteristics. The open boxes represent bit error rates in groove after crosswrite from land to groove and the open circles represent bit error rates on land after crosswrite from groove to land. A recording power margin is defined by overwrite and crosswrite characteristics and is therefore estimated by the value between two curved lines with the different shaped markers from each other in the case of Fig. 7. The recording power tolerances are 5.48 mW +/- 16.0 % on land and 5.00 mW +/- 20.0 % in groove.

Figures 8 and 9 show the tolerances with tangential tilt and with radial tilt, respectively. In both cases, the same magnitude of tilt was added during both readout and recording. Laser power was adjusted at each tilt angle. The radial tilt tolerance includes an influence of detrack because the push-pull method was used for tracking. Sufficiently wide tolerances of the tilt angle are obtained in both tangential and radial cases. The tangential tilt margins are +/- 0.76 degrees on land and +/- 0.68 degrees in groove and the radial tilt margins are +/- 0.58 degrees on land and +/- 0.66 degrees in groove. When the tilt exists during only readout, both tilt margins are more than +/- 1.0 degrees on land and in groove.

Figure 10 shows the tolerance with a track offset in two cases. Solid lines correspond to the case with a track offset during only readout. Broken lines correspond to the case with a track offset in the same direction during both readout and recording. The latter case is confirmed to be the worst case of track offset. In the case with a track offset during only readout, the detrack margins are +/- 92 nm on land and +/- 90 nm in groove. In the case with a track offset in the same direction during both reading and writing, the detrack margins are +/- 44.5 nm on land and +/- 40.5 nm in groove. Even in the worst case, good tolerances are obtained on land and in groove.

Table 3 summarizes system tolerances at 15 Gbit/in^2 using a 660 nm-laser, a 0.60 NA-objective lens and other experimental conditions as shown in table 2. Wide margins of laser powers, tilt angles and detrack are obtained and available for practical use.

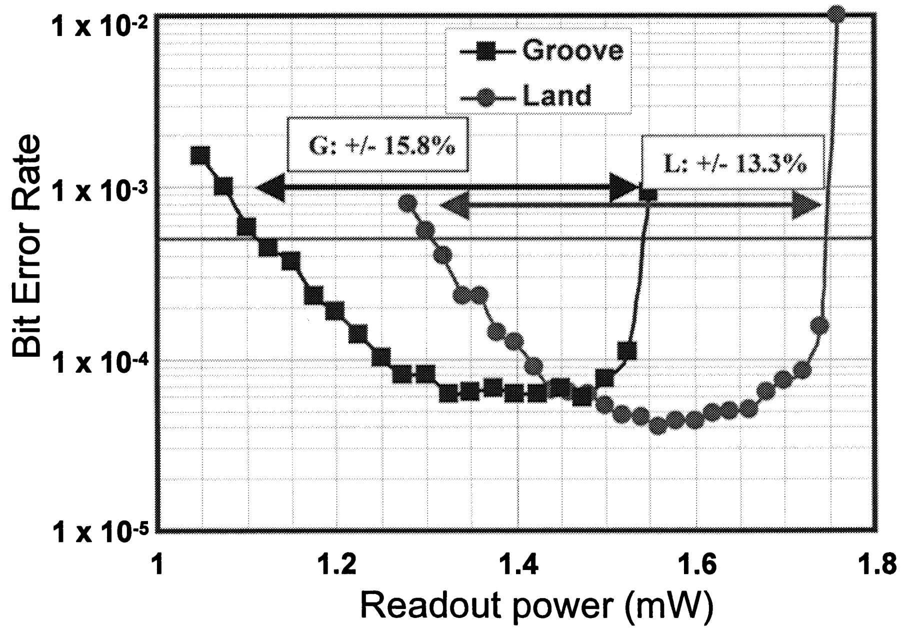

Figure 6: Readout power tolerance.

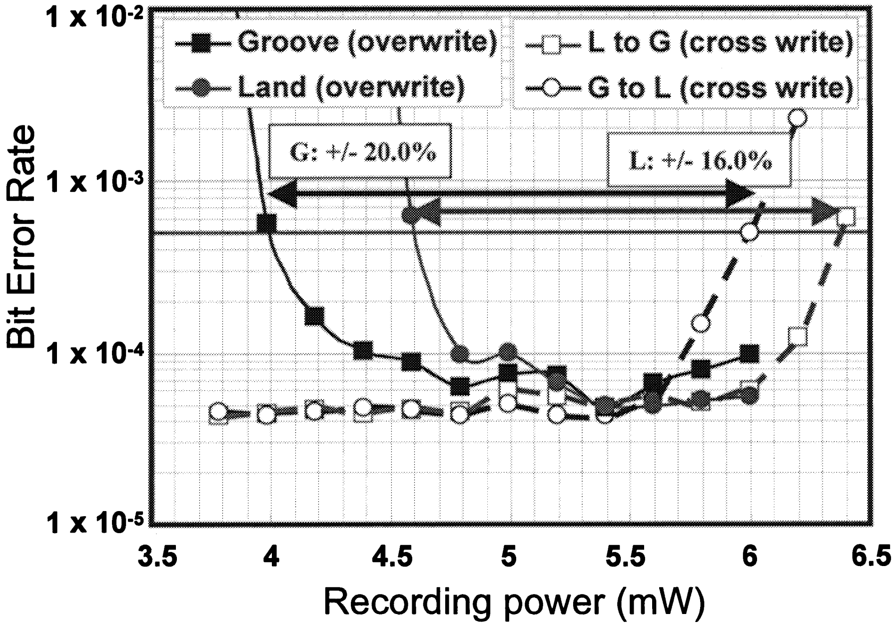

Figure 7: Recording power tolerance.

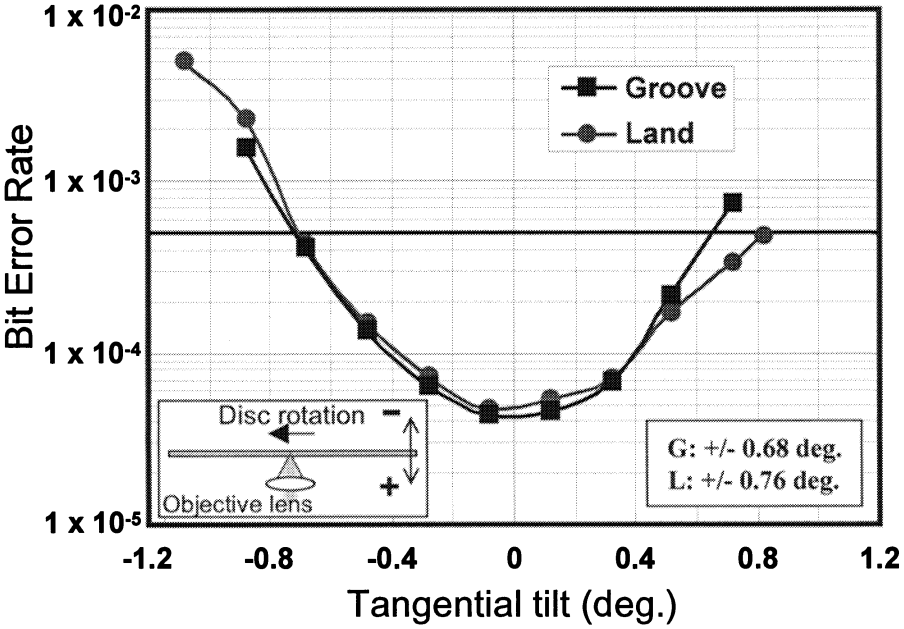

Figure 8: Tangential tilt tolerance.

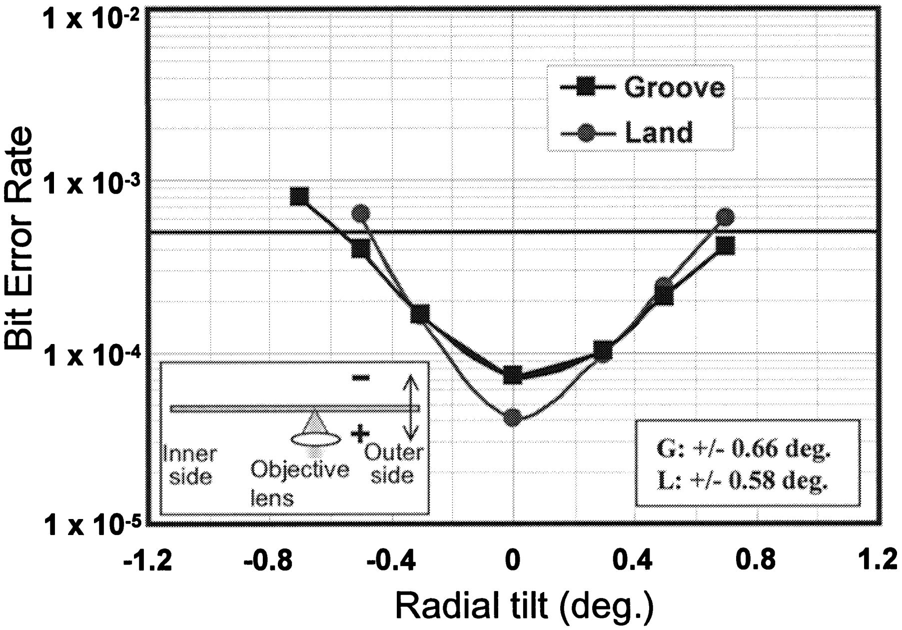

Figure 9: Radial tilt tolerance.

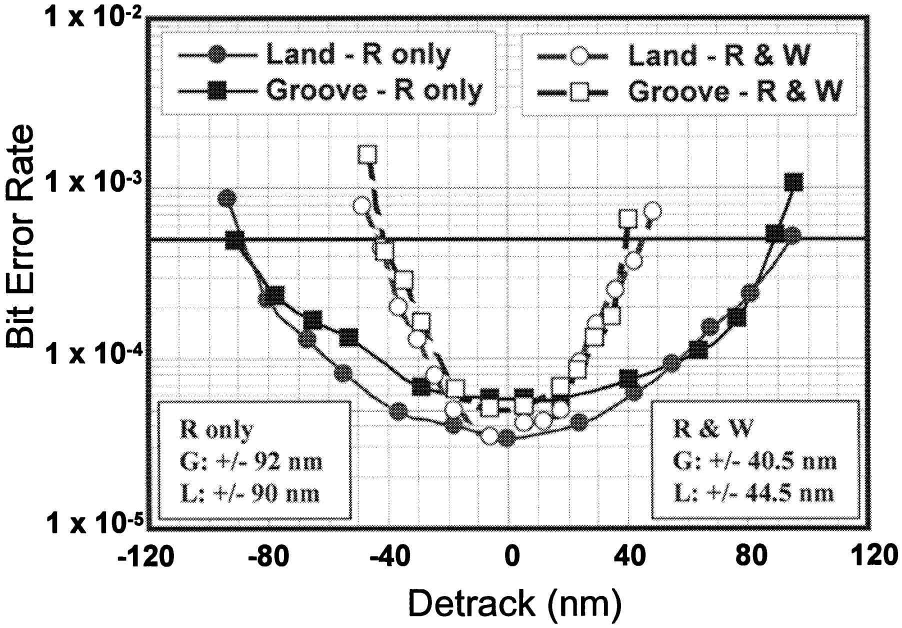

Figure 10: Detrack tolerance.

		Land	Groove
Read power		+/- 13.3 %	+/- 15.8 %
Write power		+/- 16.0 %	+/- 20.0 %
Tangential Tilt (deg.)	Read	> +/- 1.0	> +/- 1.0
	Read / Write	+/- 0.76	+/- 0.68
Radial Tilt (deg.)	Read	> +/- 1.0	> +/- 1.0
	Read / Write	+/- 0.58	+/- 0.66
Detrack (nm)	Read	+/- 92	+/- 90
	Read / Write	+/- 44.5	+/- 40.5

Table 3: Margin summary.

3.3 Prospect of our future work

In future work, we will reduce the required magnetic field and improve other characteristics more. We achieved 80 nm/bit with sufficiently low bit error rate using an anneal-less DWDD medium in this study but a limit of the shortest bit length available for practical use has not been confirmed yet. To shorten the bit length more, it should be studied how to record a tiny domain stably and how to obtain a good domain wall motion even at the shorter bit length. The study is based on the magnetic film design considering the spatial profile of magnetic properties and exchange coupling between films when the temperature distribution is varied. A substrate, a film deposition and something else may be also necessary to be improved more in order to shorten a track pitch.

4. CONCLUSION

"Anneal-less" DWDD MO medium with land-groove recording are improved by the optimum magnetic film design and the substrate which has a smooth surface and a deep groove with a unique form achieved by the RIE mastering. Using a 660 nm-laser, a 0.60 NA-objective lens and the anneal-less medium, a high areal density of 15 Gbit/in^2 was achieved with wide system tolerances for practical use. The areal density of 15 Gbit/in^2 corresponds to 4.7 GB-capacity on a disc with 64 mm-diameter like MiniDisc.

ACKNOWLEDGEMENT

We are very thankful to Minoru Takeda and Akinori Kato (Meitec corporation) for their technical support of manufacturing the RIE substrate and measuring AFM image. We are also thankful to Shinichi Kai, Yasuyuki Takeshita, Goro Fujita and Takeshi Miki for their technical support of the experimental setup and effective discussion and thankful to Osamu Kawakubo, Masanobu Yamamoto and Tadao Yoshida for their encouragement and effective suggestions.

REFERENCES

1. T. Shiratori, et al.: "HIGH-DENSITY MAGNETO-OPTICAL RECORDING WITH DOMAIN WALL DISPLACEMENT DETECTION," J. Mag. Soc. Jpn., **22** Supp. No. S2, 47-50 (1998)
2. G. Fujita, et al.: "Domain Wall Displacement Detection Mini Disc with Land/Groove Recording Applied to Mini Disc System," Jpn. J. Appl. Phys. **41**, 1643-1646 (2002)
3. O. Koyama, et al.: "Physical Characteristics and Format of a Two-Inch-Diameter Magneto-Optical Disk System with 3GB Capacity," Jpn. J. Appl. Phys. **42**, 784-791 (2003)
4. T. Sakamoto, et al.: "20 Gbit/inch^2 DWDD medium with 405nm and 0.60NA optics," in Technical Digest of ODS2001, 73-75 (2001)