An Attempt of Combining Super-Resolution and Multi-Layer Stacking Technologies for Achieving Higher Recording Capacity

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ABSTRACT

Super-resolution (SR) technology increases the recording capacity along the in-plane direction of an optical disk, and multi-layer stacking technology increases the capacity along the depth direction. Opaqueness of the optical-disk material often used for SR was a problem when combining these two technologies, and we have attempted to use indium antimony oxide (IAO) that is nearly transparent. Both recording and SR readout was possible using ZnS-SiO_2/IAO/ZnS-SiO_2 structure, and we have achieved a CNR of nearly 40 dB at 112 nm marks using BD-based optics. We further examined to stack ten ZnS-SiO_2/IAO/ZnS-SiO_2 structures (L0–L9), and CNRs of 32 dB and 21 dB were obtained at 113 nm and 75 nm marks, respectively, when evaluated at the L5 recording layer.

Key words: Super-Resolution, Multi-Layer, InSb, Oxide, CNR

1. INTRODUCTION

Increasing of the recording capacity (>128 GB) is quite important for the optical disk to be used more frequently in the archival storage field, and there are many reports studying towards the depth direction of the disk. Kikukawa *et al.* have stacked 16 recording layers, carefully controlling the reflectance of each layer, and have achieved more than 500 GB capacity in total [1]. Pudavar *et al.* have used a thick uniform layer instead, and recorded marks by modifying depth position of the laser focal point using a two-photon absorption technique [2]. On the other hand, super-resolution (SR) technology is promising when increasing the capacity along the in-plane direction of the disk [3, 4], and one may consider its combination with the multi-layer stacking method. However, Sb-based material (e.g., Sb-rich Te and InSb) that is often used for SR readout is basically opaque at the laser wavelength (e.g., extinction coefficient, k>2 at 405 nm), and not so many layers can be stacked when retrieving each recording layer from one side. This study is an attempt of the combination by introducing oxygen to InSb (hereinafter, indium antimony oxide, IAO) for higher optical transmittance. Although there are still many problems need to be solved, we would like to describe in this paper what we have achieved so far.

2. EXPERIMENTAL

For the IAO film preparation, an $In_{20}Sb_{20}O_{60}$ target (3 inch diameter, at%) with four InSb chips (5 x 5 mm) attached was used to sputter in Ar gas atmosphere. An IAO film that is sandwiched by ZnS-SiO_2 films was used for recording (and also for the SR readout), and we hereinafter call this film-stacked structure (i.e., ZnS-SiO_2/IAO/ZnS-SiO_2) as a "recording layer". For the spacing and capping layers of the disk sample, a UV resin was spin-coated and then cured. Two optical disk samples were prepared for the study. Stacking structure of the first disk (hereinafter, Disk A) was cover layer/ ZnS-SiO_2 91 nm/ IAO 20 nm/ ZnS-SiO_2 34 nm/ polycarbonate disk substrate (groove pitch: 400 nm). The disk properties were evaluated using an optical disk drive tester (ODU-1000, Pulstec Industrial) with a laser wavelength (λ) and a numerical aperture (NA) of 405 nm and 0.85, respectively. The second disk (hereinafter, Disk B) was a ten recording-layer sample, and the stacking structure is as shown in Fig. 1. For the recording layers of L0–L9, film thicknesses of ZnS-SiO_2, one of the two on the cover-layer side, and IAO were adjusted in the range of 91–122 nm and 5–20 nm, respectively, while it of ZnS-SiO_2, one of the two on the substrate side, was fixed at 34 nm. This film-thickness modification was to make the reflectance from each recording layer constant at about 1.7% when assuming k=0.5 for IAO film at λ= 405 nm [1]. Spacing layer thickness was not kept constant to reduce the interference effect from the recording layers [5]. For the disk property evaluation of Disk B, we have newly developed a system that is capable for both multi-layer recording and SR readout. The system uses a red laser (λ= 660 nm) for tracking and a blue laser (λ= 405 nm) for recording and readout [6]. Thus a DVD-based substrate was used for Disk B, and $Ag_{98}Pd_1Cu_1$ (APC, 10 nm) layer was first deposited on the substrate for the red laser reflection. Further details on the system can be found in our previous report [7].

3. RESULTS AND DISCUSSIONS

Rutherford backscattering spectrometry of the IAO film sample showed that the composition ratio was $In_{20.9}Sb_{16.9}O_{62.2}$. Refractive indices of the IAO film was n= 2.4–2.6 and k= 0.1–0.5 at λ= 400–405 nm. We first preferred to use an IAO film that contains much smaller amount of oxygen, e.g., 5–20 at%. In that case, a good SR readout property that is similar to InSb [4] may still be expected; however, k value was in need to be low (close to zero) to stack ten recording layers. The $In_{20}Sb_{20}O_{60}$ composition is when both In and Sb completely oxidize (i.e., In_2O_3+Sb_2O_3) [8], and we selected the composition near this value since high optical transparency is expected. Reducing the number of stacking layers while keeping the oxygen content low was another choice; however, capacity increment rate is often much faster for the multi-layer stacking compared to the SR readout, and we thus kept the stacking layer number to be a high value of "ten" in this study. It should be noted that reproducibility of making the IAO film was still not sufficient, and the k value varied in the range shown above.

Figure 2(a) shows carrier-to-noise ratio (CNR) properties of Disk A as a function of marklength. For the marks longer than 3T (when T= 56.25 nm), fairly high CNRs at about 50 dB were obtained. The disk was rotated at a constant linear velocity of 2.46 m/s. Recording mechanism of the disk is not exactly understood; however, we have found that the IAO film itself shows an "irreversible" optical property change at λ= 405 nm when it is heated (not shown). There was also an increase of the film thickness when ZnS-SiO_2/IAO/ZnS-SiO_2 structure is heated up to 600 ˚C, and it suggests that the interaction between IAO and ZnS-SiO_2 layers might took place when recording. We note that crystallization and a dramatic oxygen content variation were not both recognized for the IAO film when heated to 600 ˚C. 2T marks (112 nm) in Fig. 2(a) is slightly shorter than the resolution limit of the optics (λ/4NA= 119 nm) used, and thus CNR was low (24 dB) when the readout laser power (Pr) was low at 1.0 mW. Figure 2(b) shows CNR properties of Disk A when Pr is increased from 1.0 mW for the 2T mark. CNR gradually increased as a function of Pr and reached nearly 40 dB at Pr= 2.6 mW. SR readout mechanism of the disk is also not well understood at the moment. We so far could not find any "reversible" optical property change in the IAO film. A CNR trend of gradual increase for the marklength near the resolution limit is similar to the previously reported one of ZnO [9], and a semiconductor-like property [10] might be related to the SR readout mechanism at the mark and/or the space of the recording layer. CNR properties were not as good as the one of InSb [4], and we believe that a large optical contrast of InSb induced by melting [11] is basically lost for the oxides. Although further basic studies on the mechanisms are indispensable, we would like to emphasize that the recording layer, i.e., ZnS-SiO_2/IAO/ZnS-SiO_2 was nearly transparent and can be used not just for recording but also for the SR readout.

Based on the experimental results in Fig. 2(b), we have stacked ten recording layers as shown in Fig. 1. We have succeeded in focusing and tracking all the recording layers using both red and blue lasers. Figure 3 shows the reflectance values from each recording layer obtained experimentally. Presumably due to the optical-property fluctuation of the IAO film preparation, the reflectance value varied in the range of 1.1–2.6%. Figure 4 shows CNR of 2T marks (113 nm) recorded at the L5 recording layer. CNR was low (10 dB) when Pr= 1.0 mW (Fig. 4(a)), but it increased to 32 dB when Pr= 4.0 mW (Fig. 4(b)). We have also recorded 75 nm marks at the L5 recording layer, and CNR increased from 0 to 21 dB when Pr is increased from 1.0 to 4.0 mW. The results demonstrated that both recording and SR readout were possible in the multi-layer stacked optical disk sample. It should be noted that similar SR readout properties could be obtained at only between L2 and L5 for Disk B. Recording (and/or SR readout) power was probably not enough for L0 and L1, and tracking servo was not so stable for L6–L9 presumably as a result of stacking "many" layers. However, the problems are mostly due to the optical disk sample preparation, and the evaluation system itself was basically capable for both recording and SR readout of at least of ten recording layers.

4. CONCLUSION

We have examined the combination of multi-layer stacking and SR readout technologies to achieve higher recording capacity. We have shown that $In_{20.9}Sb_{16.9}O_{62.2}$ film sandwiched by ZnS-SiO_2 films can be used for both recording (~50 dB @≥169 nm) and SR readout (~40 dB @112 nm) using BD-based optics. We have prepared an optical disk sample (Disk B) stacking ten recording layers of ZnS-SiO_2/$In_{20.9}Sb_{16.9}O_{62.2}$/ZnS-$SiO_2$ and succeeded in focusing and tracking of all the recording layers. So far, both recording and SR readout were possible at between L2–L5, and CNRs of 32 dB and 21 dB were obtained at 113 nm and 75 nm marks, respectively, when evaluated at the L5 recording layer.

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REFERENCES

[1] T. Kikukawa *et al.*, Jpn. J. Appl. Phys. **49** (2010) 08KF01.
[2] H.E. Pudavar *et al.*, Appl. Phys. Lett. **74** (1999) 1338.
[3] T. Shima: in *Optical memory and its system for next generation*, ed. Y. Okino (CMC Publishing, Tokyo, 2009) Chap. 3-5, p.152, and references therein.
[4] G. Pilard *et al.*, Jpn. J. Appl. Phys. **48** (2009) 03A064.
[5] J. Ushiyama *et al.*, Jpn. J. Appl. Phys. **47** (2008) 3499.
[6] M. Ogasawara *et al.*, Jpn. J. Appl. Phys. **50** (2011) 09MF01.
[7] http://www.chusho.meti.go.jp/keiei/sapoin/portal/seika/2010/22131803112.pdf
[8] T.P. Smirnova *et al.*, Thin Solid Films **76** (1981) 11.
[9] M. Yamamoto *et al.*, Jpn. J. Appl. Phys. **43** (2004) 4959.
[10] N. Kikuchi *et al.*, Vacuum **65** (2002) 81.
[11] B. Hyot, Phys. Status Solidi B **249** (2012) 1992.

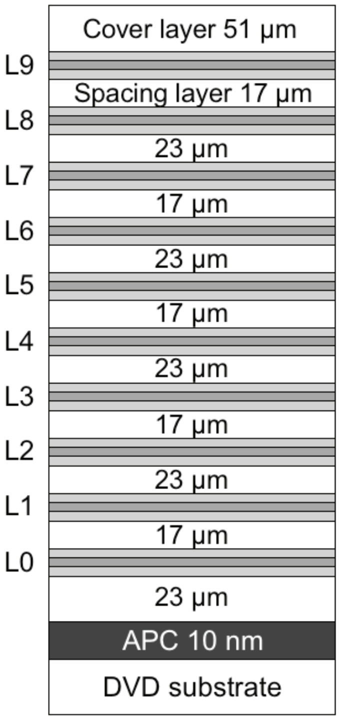

Figure 1 Stacking structure of Disk B. Lx (x=0–9) are the recording layers and each consists of $ZnS\text{-}SiO_2$/IAO/$ZnS\text{-}SiO_2$.

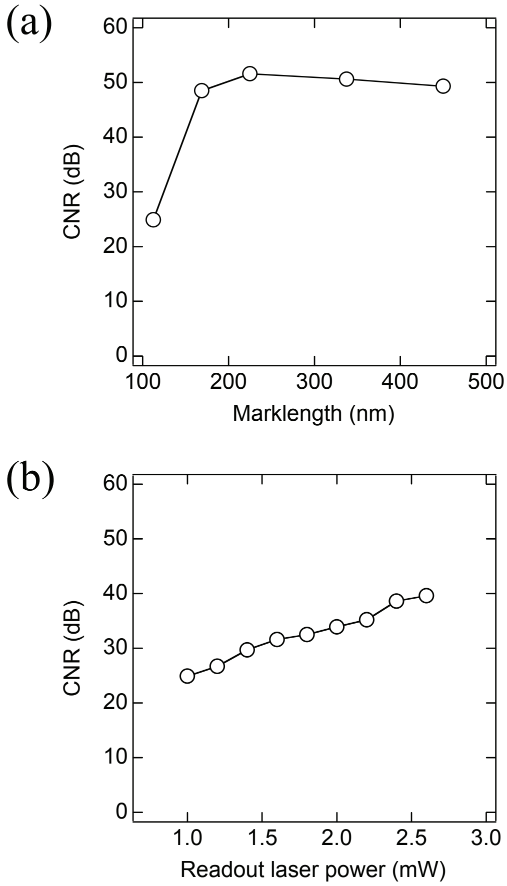

Figure 2 CNR properties of Disk A as a function of mark length (a) and readout laser power for the 112 nm mark (b).

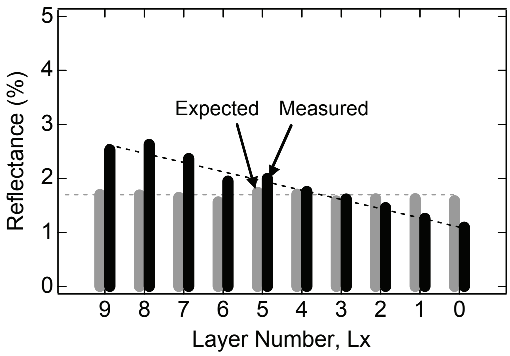

Figure 3 Reflectance of each recording layer (L0–L9) for Disk B (gray: expected, black: measured).

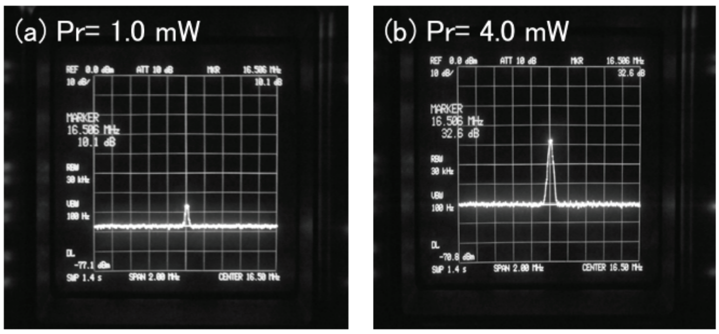

Figure 4 CNR of 113 nm marks for Disk B at L5. Readout laser power (Pr) was 1.0 mW (a) and 4.0 mW (b).