Study of the optical response of phase-change recording layer with zinc oxide nanostructured thin film

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Summary

Recently, use of nanostructured materials as a near-field optical active layer has attracted a lot of interest. The non-linear optical properties and strong enhancements of metallic oxide nanostructured thin films are key functions in applications of promising nanophotonics. For the importance of ultra-high density optical data storage, we continue investigating the ultra-high density recording property of near-field optical disk consisting of zinc oxide (ZnO_x) nanostructured thin film. A carrier-to-noise ratio above 38 dB at a recording mark size of 100 nm can be obtained in the ZnO_x near-field optical disk by a DVD driver tester directly. In this article, we use an optical pump-probe system (static media tester) to measure the optical response of a phase-change recording layer (Ge₂Sb₂Te₅) and demonstrate the high contrast of optical recording with a ZnO_x nanostructured thin film in short pulse durations. Also, we investigate the dependence of writing power and the optical response in conventional re-writable recording layers and the phase-change material with ZnO_x nanostructured thin film.

Introduction

A wide band gap of 3.37 eV and a large excitonic binding energy of 60 meV have made zinc oxide (ZnO) a promising photonic material for developing short-wavelength optical devices (Bagnall *et al.*, 1997). Nanostructured ZnO has attracted manifold interest recently for its room-temperature blue-UV lasing and wide optoelectronic applications (Cao, Xu,

Seelig, *et al.*, 2000; Cao, Xu, Zhang, *et al.*, 2000; Wiersma, 2000; Huang *et al.*, 2001). To pursue ultra-high density optical recording ability, a promising method that uses a metallic oxide nanostructured thin film as a near-field optical active layer to promote and enhance signals between adjacent recording marks has been studied in several types of near-field optical disks with metallic oxide nanostructured thin films (Tsai & Lin, 2000; Tsai *et al.*, 2000; Liu *et al.*, 2001; Yu *et al.*, 2004; Fu *et al.*, 2006). To achieve our purpose of ultra-high density recording ability, we prepare sputtered ZnO_x nanostructured thin film as a near-field optical active layer to attain ultra-high density recording. A carrier-to-noise ratio (CNR) above 38 dB at the recording mark size of 100 nm can be measured by a conventional DVD driver tester (DDU-1000, Pulstec) with a wavelength of incident laser of 658 nm (λ) (Lin *et al.*, 2003). The read-out signals of ZnO_x-type near-field optical disk and the nanostructure of a ZnO_x nanostructured thin film are studied as well. To investigate the optical properties of ZnO_x nanostructured thin film and its potential applications, we use an optical pump-probe system (static media tester, Toptica) to investigate the optical responses of a phase-change material (Ge₂Sb₂Te₅) with sandwiched ZnO_x nanostructured thin film, and the results are compared with that of conventional re-writable recording layers.

Materials and methods

Preparation of ZnO_x nanostructured thin-film samples with different layered structure

ZnO_x nanostructured thin film is prepared by the RF-magnetron reactive sputtering method. Pure Zn (purity: 4 N, diameter: 76 mm) is used as a target, and gas flows of Ar and

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Fig. 1. The scheme of prepared samples with different layered structures. (a) Sandwiched ZnO_x nanostructured thin film: glass \ ZnS-SiO_2 \ ZnO_x \ ZnS-SiO_2 ; (b) conventional recording layered structure: glass \ ZnS-SiO_2 \ $\text{Ge}_2\text{Sb}_2\text{Te}_5$ \ ZnS-SiO_2 ; (c) ZnO_x -type near-field optical disk structure: glass \ ZnS-SiO_2 \ ZnO_x \ ZnS-SiO_2 \ $\text{Ge}_2\text{Sb}_2\text{Te}_5$ \ ZnS-SiO_2 .

O_2 are precisely regulated, respectively. The thickness of ZnO_x nanostructured thin film can be precisely controlled by the sputtering rate ($1.38 \text{ \AA s}^{-1}$ for ZnO_x) and time. Sputtering power and pressure are fixed at 200 W and 0.5 Pa. As showed in Fig. 1, the layered structures that we studied are sandwiched ZnO_x nanostructured thin film, cover glass \ ZnS-SiO_2 (130 nm) \ ZnO_x (15 nm) \ ZnS-SiO_2 (40 nm); conventional rewritable recording layer, cover glass \ ZnS-SiO_2 (130 nm) \ $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (20 nm) \ ZnS-SiO_2 (20 nm) and ZnO_x -type near-field optical disk structure, that is, phase-change recording layer with ZnO_x nanostructured thin film, cover glass \ ZnS-SiO_2 (130 nm) \ ZnO_x (15 nm) \ ZnS-SiO_2 (40 nm) \ $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (20 nm) \ ZnS-SiO_2 (20 nm).

Optical pump-probe system (static media tester)

After the preparation of ZnO_x nanostructured thin film with different layered structure, we use an optical pump-probe system (static media tester, Toptica) to measure the optical response on a phase-change recording layer ($\text{Ge}_2\text{Sb}_2\text{Te}_5$). The scheme of the experimental set-up is shown in Fig. 2. The wavelength of pulse laser for writing is 658 nm and that of CW laser for reading is 633 nm. The writing power is changed from 1 to 20 mW and the reading power is fixed at 0.6 mW. The writing laser power and pulse duration are controlled during the recording process. The time evaluated reflectance signal of writing laser and reading laser from the sample are monitored simultaneously. The CCD camera with an objective lens (N.A. = 0.6, $40\times$) can be used to observe the structural change and reflectance variation on the surface of irradiated phase-change recording layer.

Results and discussion

Figure 3 shows the TEM image (cross-section, Fig. 3(a)) and electron diffraction pattern (Fig. 3(b)) of the sandwiched zinc oxide (ZnO_x) nanostructured thin film (JEM-4000EX HR-TEM, JEOL). The layered structure of ZnO_x nanostructured thin film is silicon \ ZnS-SiO_2 (130 nm) \ ZnO_x (15 nm) \ ZnS-SiO_2 (40 nm). In Fig. 3(a), the ZnO_x nanostructured thin film looks like nanoteeth sandwiched by two dielectric thin films (ZnS-SiO_2). The diameter of the ZnO_x nanotooth is about 8 nm

and its growing direction is about $12\text{--}13^\circ$ deviated from the normal. This interesting property reported by Huang and co-workers (Cao, Xu, Seelig, *et al.*, 2000; Cao, Xu, Zhang *et al.*, 2000) may imply that the novelty of the nanowire or nanorod could be applied to the ZnO_x nanostructured thin film of ZnO_x -type near-field optical disk (Chu *et al.*, 2005, 2007). Thus, it is suggested that the ensemble effects of these ZnO_x nanostructures are the key factors for induction of the ultra-high density recording ability observed in our study. Fig. 3(b) shows the electron diffraction pattern of the sandwiched ZnO_x nanostructured thin film. It indicates that the orientation of crystalline ZnO_x nanoteeth is (101) (Pan *et al.*, 2001; JCPDS file 36-1451).

Figure 4 shows the CCD image and reflectance variation of sandwiched ZnO_x nanostructured thin film with different incident pulse power (both including writing and reading power). The pulse power is changed from 1 to 20 mW and the pulse duration is fixed at 50 μs . In the results of CCD image and reflectance variation, no matter how much higher is the pulse power applied, the appearance of CCD image and the variation of optical reflectance remain the same. The invariability of appearance and reflectance indicates that there is no heat accumulation or destruction on sandwiched ZnO_x nanostructured thin film. Moreover, the pulse power of 20 mW and the pulse duration of 50 μs are much higher and longer than the conventional writing strategy on optical disks. It means that the ZnO_x nanostructured thin film is a thermal stable material using in ultra-high density recording (Pan *et al.*, 2001).

In the comparison of optical response of conventional rewritable recording layered structure and the phase-change material ($\text{Ge}_2\text{Sb}_2\text{Te}_5$) with ZnO_x nanostructured thin film, we intend to investigate the optical variation on the phase-change recording layer with different writing power (1–20 mW) and pulse duration (50–1000 ns). In the results of short pulse duration ($t = 50 \text{ ns}$), Fig. 5 shows the CCD images of conventional re-writable recording layer and ZnO_x -type near-field optical disk structure, respectively. In Fig. 5(a), the CCD image of conventional re-writable recording layer shows that there is no obvious recording mark produced in such a short pulse duration. However, in Fig. 5(b), the recording

Fig. 2. The experimental set-up of an optical pump-probe system (static media tester, Toptica).

marks can be observed and the contrast of recording mark can be increased with a ZnO_x nanostructured thin film. The ZnO_x nanostructured thin film not only shortens the time of phase-change recording mark formation but also promotes the contrast of read-out ability.

Figs 6 and 7 show the CCD images and the reflectance of recording marks on conventional re-writable recording layered structure ($\text{Ge}_2\text{Sb}_2\text{Te}_5$) and the phase-change material with ZnO_x nanostructured thin film, respectively. The writing power is changed from 1 to 20 mW and the pulse duration is fixed at 200 ns. Figure 6(b) shows the reflectance variation in pulse duration with writing and reading power. The contrast Δ denotes the difference of optical reflectance of reading power before and after incident pulse laser irradiation. During the irradiation of incident pulse laser, the optical reflectance of higher writing power (> 15 mW) decreases step by step and

the contrast Δ increases with writing power. The occurrence of decreasing reflectance of writing power corresponds to the CCD image as showed in Fig. 6(a). As the phase-change recording layer ($\text{Ge}_2\text{Sb}_2\text{Te}_5$) is an optical and heat-based material (Miyamoto *et al.*, 1998; Ohta *et al.*, 2000; Kooi *et al.*, 2004; Lin *et al.*, 2006;), it is obvious that the decreasing reflectance of writing power comes from the structural change of destroyed hole on the surface of phase-change recording layer. The diameter of destroyed hole depends on the power of incident pulse laser (20 mW, 1.464 μm ; 15 mW, 1.440 μm). The increasing diameter of destroyed hole gives the evidence of increasing contrast with increasing incident pulse power. In the comparison of optical response of phase-change material with ZnO_x nanostructured thin film (Fig. 7), the contrast is more distinguishable than that of the conventional re-writable recording layer at the same power of incident pulse

Fig. 3. (a) The TEM image (cross section) and (b) electron diffraction pattern of sandwiched ZnO_x nanostructured thin film. (JEM-4000EX HR-TEM, JEOL).

Fig. 4. The optical response of sandwiched ZnO_x nanostructured thin film. The power of pulse laser is changed from 1 to 20 mW and the pulse duration is 50 μ s.

laser and also increases with incident writing power. The higher contrast shows the reflectance promotion of the ZnO_x nanostructured thin film. In the higher writing power (> 15 mW), the reflectance of writing power also decreases step by step. However, in Fig. 7(a), the CCD image of the recording mark shows structural change of destroyed hole, with a tiny bright spot produced at the centre on the surface of the phase-change recording layer. The diameter of the destroyed hole and that of the tiny bright spot both depend on the writing power (destroyed hole: 20 mW, 1.545 μ m; 15 mW, 1.486 μ m; tiny bright spot: 20 mW, 0.759 μ m; 15 mW, 0.750 μ m). Because

the sandwiched ZnO_x nanostructured thin film is independent from the power of incident pulse laser and pulse duration (as the results of Fig. 4), there is no heat accumulation or structural change on sandwiched ZnO_x nanostructured thin film. The tiny bright spots are produced at the phase-change recording material (Ge₂Sb₂Te₅) with the ZnO_x nanostructured thin film.

Figure 8 shows the comparison of the reflectance contrast with different applied pulse writing power on a conventional re-writable layered structure and the phase-change material with ZnO_x nanostructured thin film. The pulse writing power is changed from 1 to 20 mW and the pulse duration is

Fig. 5. The comparison of CCD images with different layered structure. (a) Conventional re-writable recording layered structure: glass \ ZnS-SiO₂ (130 nm) \ Ge₂Sb₂Te₅ (20 nm) \ ZnS-SiO₂ (20 nm); (b) ZnO_x-type near-field optical disk structure: glass \ ZnS-SiO₂ (130 nm) \ ZnO_x (15 nm) \ ZnS-SiO₂ (40 nm) \ Ge₂Sb₂Te₅ (20 nm) \ ZnS-SiO₂ (20 nm). The power of pulse laser is changed from 1 to 20 mW and the pulse duration is 50 ns.

Fig. 6. The optical response of conventional re-writable recording layered structure in a pulse duration of 200 ns.

Fig. 7. The optical response of ZnO_x -type near-field optical disk structure in a pulse duration of 200 ns.

Fig. 8. The comparison of the highest contrast in different pulse durations with different layered structures. (a) conventional re-writable recording layered structure and (b) ZnO_x -type near-field optical disk structure.

changed from 50 to 1000 ns. In Fig. 8(a), the reflectance contrast depends on the pulse duration and the pulse writing power. First, with the longer irradiation of incident pulse laser, the higher reflectance contrast of recording mark can be obtained. It indicates that the heat accumulation and structural change on the phase-change ($\text{Ge}_2\text{Sb}_2\text{Te}_5$) recording layer. Furthermore, in the irradiation of higher incident pulse power (higher than 10 mW), the reflectance contrast is more distinguishable and increases with pulse duration step by step. The step increasing of reflectance contrast means that the structural change and the heat diffusion are not homogeneous on the phase-change recording layer. The multiple stages of reflectance change also provides an advantage in multi-level recording. In the comparison of reflectance contrast on phase-change recording layer with the ZnO_x nanostructured thin film, the contrast is more distinguishable and stable than that on the conventional re-writable recording layer at the same writing power. The reflectance contrast does not show a great difference at long pulse durations, which indicates that there was less structural change and heat accumulation with the ZnO_x nanostructured thin film. However, the highest reflectance contrast can be obtained at short pulse durations. It means that the reflectance contrast can be promoted by the ZnO_x nanostructured thin film without the structural change on phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$.

Conclusion

In this paper, we use an optical pump-probe system (static media tester, Toptica) to demonstrate the optical response of sandwiched zinc oxide (ZnO_x) nanostructured thin film, conventional re-writable recording layer, and phase-change recording layer ($\text{Ge}_2\text{Sb}_2\text{Te}_5$) with the ZnO_x nanostructured thin film. With the high pulse writing power and the long irradiation on sandwiched ZnO_x nanostructured thin film, the CCD image and low reflectance indicate that sandwiched ZnO_x nanostructured thin film is a highly transparent and thermally stable material. In the ZnO_x -type near-field optical disk structure, the contrast and the signals of recording marks can be promoted and are more distinguishable than that on conventional re-writable recording layers. The recording marks can be produced in short pulse duration ($t = 50$ ns) and tiny bright spots can be produced at the centre of the destroyed hole on the phase-change recording layer with a ZnO_x nanostructured thin film.

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