Performance of a write-once multilayer optical disk that uses transparent recording material with an optical switching layer

Fung-Hsu Wu, Han-Ping D. Shieh, Der-Ray Huang, and Tom D. Milster

A volumetric optical disk that has multiple transparent films with optical switching layers is used as a recording medium to increase the number of recording layers. In the disk the optical switching layer is adapted to reduce decay of laser energy and increase reading and recording sensitivity. Well-defined marks of ~100-nm depth can be placed precisely on the transparent films by a focused laser beam. Writing and reading of a four-layer recordable disk, fabricated by molding and spin bonding, have been demonstrated experimentally. The volumetric disk can achieve a high recording capacity with conventional optical pickups. © 2004 Optical Society of America

OCIS codes: 210.0210, 210.4590, 210.4810, 160.4330.

1. Introduction

As the demand for storage capacity continually grows, data storage technologies are being driven to achieve higher capacity, higher readout and recording bit rates, and faster access time. The recordable optical disk used as a two-dimensional optical storage medium is currently the most widely used physical format for optical storage. A promising technique has been developed to increase the volumetric data density of optical disks by axially stacking a number of recording layers in the third physical dimension. However, issues such as interlayer cross talk, low laser-energy transmittance, and absorption exist in such a disk.[1] To resolve these issues, an optical switching layer was introduced into a volumetric optical disk.[2,3] In this paper we demonstrate that a disk structure with multiple transparent films and optical switching layers as the recording medium increases the number of recording layers in a volumetric optical disk.

F.-H. Wu, H.-P. D. Shieh (hpshieh@mail.nctu.edu.tw), and D.-R. Huang are with the Institute of Electro-Optical Engineering, National Chiao-Tung University, HsinChu, Taiwan 30010, China. T. D. Milster is with the Optical Data Storage Center, Optical Sciences Center, University of Arizona, Tucson, Arizona 85721. D.-R. Huang is also with the Opto-Electronics and Systems Laboratories, Industry Technology Research Institute, Hsin-Chu, Taiwan 310, China.

Received 31 March 2004; revised manuscript received 6 June 2004; accepted 6 June 2004.

0003-6935/04/295498-05$15.00/0

2. Disk Design

In a multilayer optical disk, laser energy is decreased by the presence of out-of-focus recording layers. The total number of recording layers is therefore limited by the maximum laser power of the pickup. We propose to use a disk structure with an intensity-dependent nonlinear optical switching layer added to each layer, as shown in Fig. 1, to modulate the absorption and transmission of light in the recording layers. Depending on where the laser is focused, the interactions between recording layers and the focused laser spot are classified into three categories: (a) very low light intensity, (b) reading, and (c) writing modes, as shown in Fig. 2. To enable data marks to be read or recorded on various recording layers, the optical switching layers should have the following nonlinear characteristics in various modes:

(a) No nonlinear phenomenon occurs as the optical switching layer is illuminated by a very low intensity out-of-focus spot. The recording layers are in a high transmittance state to suppress interlayer cross talk.

(b) Large reflected signals are obtained when the nonlinear absorption phenomenon enhances its reflectivity in the focused spot area.

(c) Nonreversible thermally deformed materials, such as polycarbonate (PC) and poly(methyl methacrylate), can be deformed if a higher power is applied.

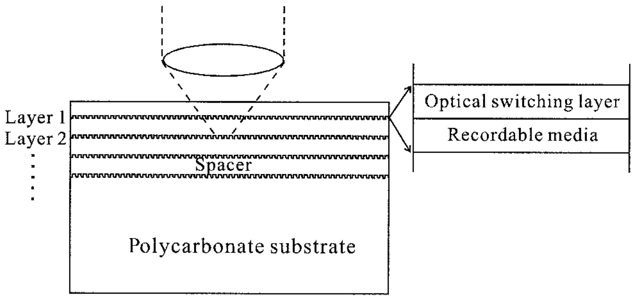

Fig. 1. Schematic diagram of an optical disk with optical switching layers.

Write-once submicrometer marks can be recorded on these transparent materials.

In the disk, the conventional low-transmittance recording material was replaced by a transparent PC sheet with a thickness of 80 μm to improve laser-energy efficiency, suppress interlayer cross talk, and increase the total number of recording layers. A triple-layer silver oxide structure, 20-nm ZnS–SiO_2/15-nm $AgO_{0.59}$/20-nm ZnS–SiO_2,[4] was chosen as the optical switching layer in the disks because of its large optical nonlinearity.[5] A cross-sectional view of the write-once multilayer disk is illustrated in Fig. 3. Specifically, this simplified structure offers a three-dimensional optical disk with significantly decreased cross talk, a large number of inexpensive recording layers on a substrate, and reduced reading–recording laser power.[4]

3. Disk Fabrication and Testing

We fabricated the disk by stacking the recording layers as illustrated in Fig. 4. First the land–groove structure for tracking was transferred from a digital versatile disk—recordable (DVD-R) stamper to an 80-μm-thick PC sheet by a molding process. A clear transferred pattern on the PC sheet can be observed by use of an atomic-force microscope (AFM), as shown in Fig. 5. Next, the PC sheets were cut to a round shape, and then a triple-layer silver oxide structure, functioning as an optical switching layer, was deposited by sputtering. Then a spacer layer consisting of a UV-resin was applied by spin coating onto a 0.6-mm-thick DVD substrate. Subsequently the recording layers were bonded by spin bounding. After UV curing, a write-once multilayer optical disk was fabricated.

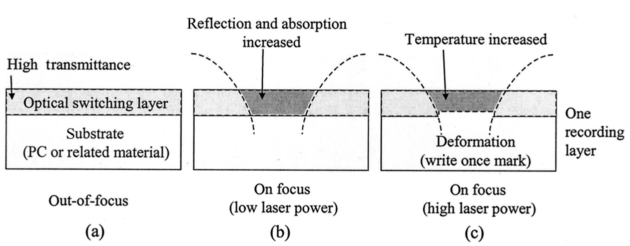

Fig. 2. Working principles of one recording layer in a write-once multilayer optical disk with optical switching layers: (a) out of focus, (b) reading, and (c) recording.

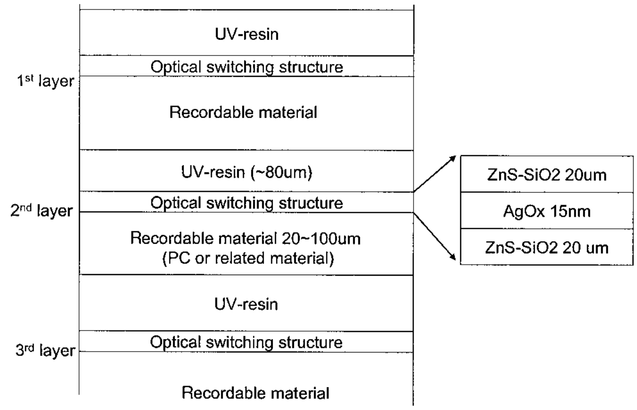

Fig. 3. Schematic of a multilayer disk structure that uses transparent recordable material with an optical switching layer.

We fabricated a four-layer sample disk to evaluate the feasibility of a write-once multilayer optical disk that uses a transparent recording material with an optical switching layer. The disk was composed of a substrate and multiple stacked recording layers consisting of PC films and a triple-layer silver oxide structure, 20-nm ZnS–SiO2/15-nm $AgO_{0.59}$/20-nm ZnS–SiO2. A dynamic disk tester that uses a 0.6-N.A. objective at 650-nm wavelength was used to analyze its read–write performance. Besides, one can generally correct the spherical aberration caused by the diverse spacer thickness while the spacer is being focused through the recording layers by tuning the compensation plate of the objective.[6]

4. Experimental Result and Discussion

For four recording layers, we used single-pulse writing strategies to write a 3T (~0.46-μm) data-mark train at a constant linear speed of 8.4 m/s. The carrier-to-noise ratio (CNR) is shown in Fig. 6 as a function of writing power at 1-mW read power. Greater than 40-dB signal intensity was obtained from the first recording layer. However, a lower signal intensity (7 dB less) was obtained from the bottom recording layer, as shown in Fig. 7. Thus, additional preamplifiers and noise filters in the data channels were needed for balancing the signals from various recording layers. A larger signal intensity difference (8 dB less) was obtained from the recording layers if the writing power was fixed at 10 mW. Therefore, further optimization of the writing power on each recording layer is needed to improve the signal qualities. Besides, the vertical depth of written marks on the first recording layer, observed by AFM and shown in Fig. 8, was ~103 nm, in the same order of data marks in a DVD ROM disk.

The multilayer disk shown in Fig. 3 was modeled by a commercial software, Diffract,[7] to simulate the readout signals from different recording layers. The optical characteristics, reflection (R) and transmittance (T) of the optical switching layer, were variables. For example, if a portion of the recording layer is in the focused spot area, R and T are 20% and

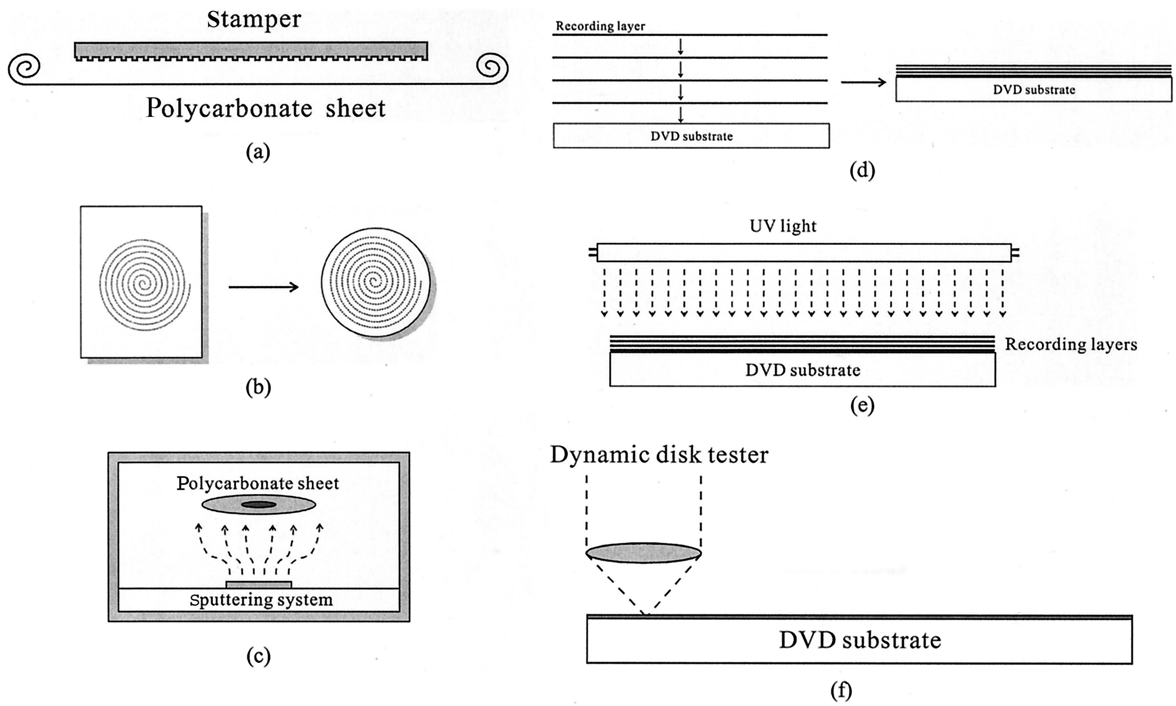

Fig. 4. Schematic illustration of the fabrication process for the multilayer disk: (a) Replicate the groove structures on the 80-μm-thick PC sheets, (b) cut the PC sheets into round shapes, (c) deposit optical switching layers onto the PC sheets by sputtering, (d) stack the recording layers on a 0.6-mm-thick DVD substrate, (e) initiate UV curing, (f) fabricated multilayer disk.

50%, respectively; otherwise, the other portion of the recording layer that is not in focus exhibits R and T of 10% and 60%, respectively.[6] The 3T mark train with a 50% duty cycle was embedded in the recording layers. The readout signal was acquired as the focused spot was scanned. The calculated readout signal is shown in Fig. 9(a). A disk without an optical switching layer was modeled as a comparison. The disk structure was similar to the previous structure, but the optical switching layer was replaced by a thin metal film. R and T were set to 10% and 60%, respectively. The calculated results, shown in Fig. 9(b), reveal an extremely low signal intensity compared with the disk-with-switching layer calculation for the bottom recording layers. These simulation results agree well with measured data. The experiment used data marks recorded at a writing power of 10 mW. The readout signals from layers 1–4 at a readout power of 1 mW are shown in Fig. 10. The signal amplitude ratios of the layers (approximately 8:4:2:1) agree with the calculated results shown in Fig. 9(a). The results indicate that the readout signals were enhanced by the optical switching layers.

5. Conclusions

A write-once multilayer optical disk that uses transparent recording materials and nonlinear optical switching layers has been demonstrated; it achieves a large data capacity on a single disk substrate. In such a disk the optical switching layer is designed to modulate the laser energy distribution and enhance the readout signals. A four-layer recordable disk was

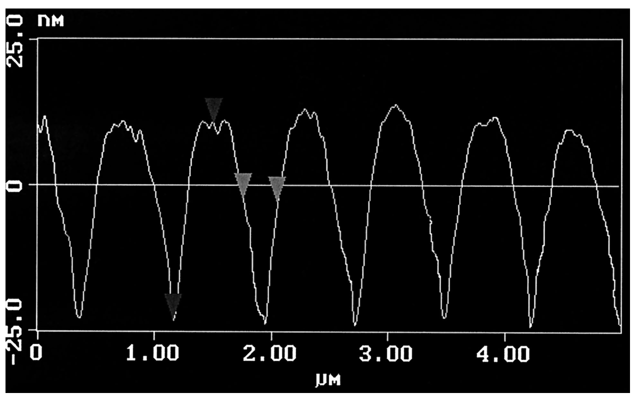

Fig. 5. AFM profile of transferred land–groove structure on a thin PC sheet.

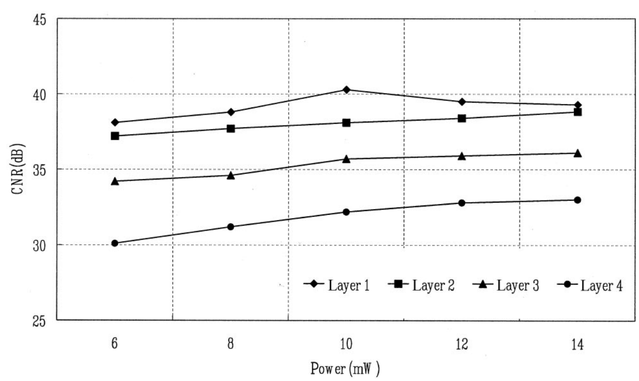

Fig. 6. CNR as a function of writing power in four recording layers.

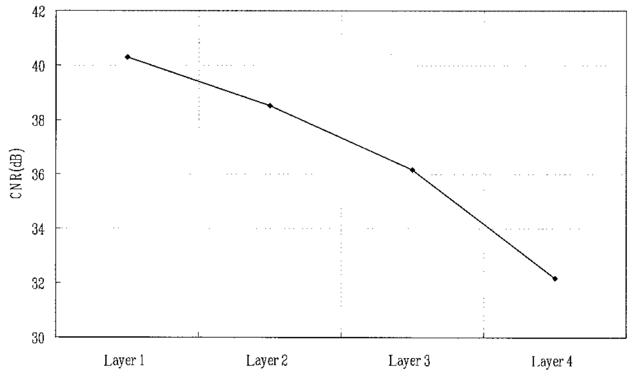

Fig. 7. CNR of recording layers at a writing power of 10 mW.

designed and fabricated for writing–reading tests. We used a writing power of 10 mW to write 3T data marks, and a CNR of more than 32 dB was obtained. Therefore, transparent recording material with an optical switching layer can be used to reduce writing laser power and increase the number of recording layers in a volumetric disk.

This research was supported by the Ministry of Education of the Republic of China under the Program for Promoting Academic Excellence of University in "Photonics Science and Technology for Tera Era" under grant 89-E-FA06-1-4. We appreciate technical support from Tzuan-Ren Jeng of the Opto-Electronics and Systems Laboratories, Industrial Technology Research Institute of Taiwan.

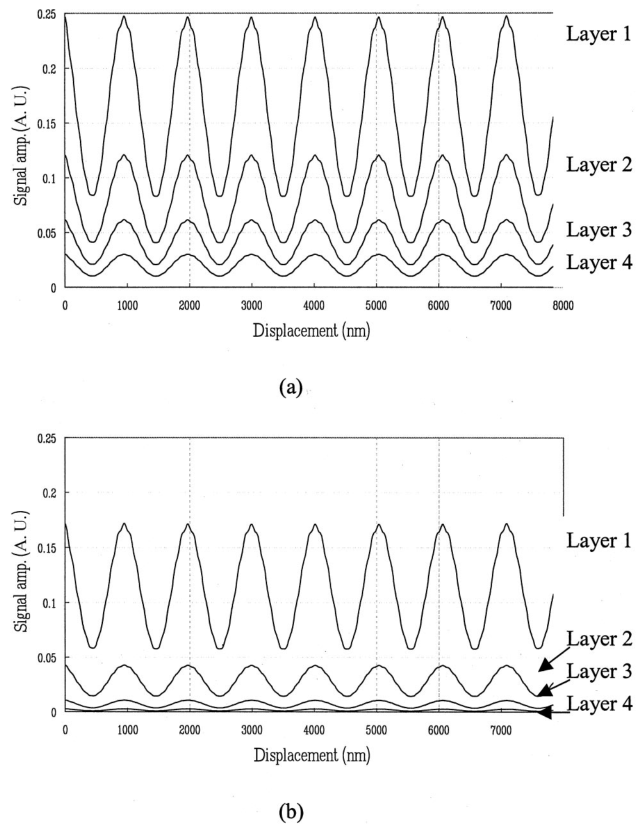

Fig. 9. Calculated readout signal from recording layers of the disk (a) with and (b) without optical switching layers.

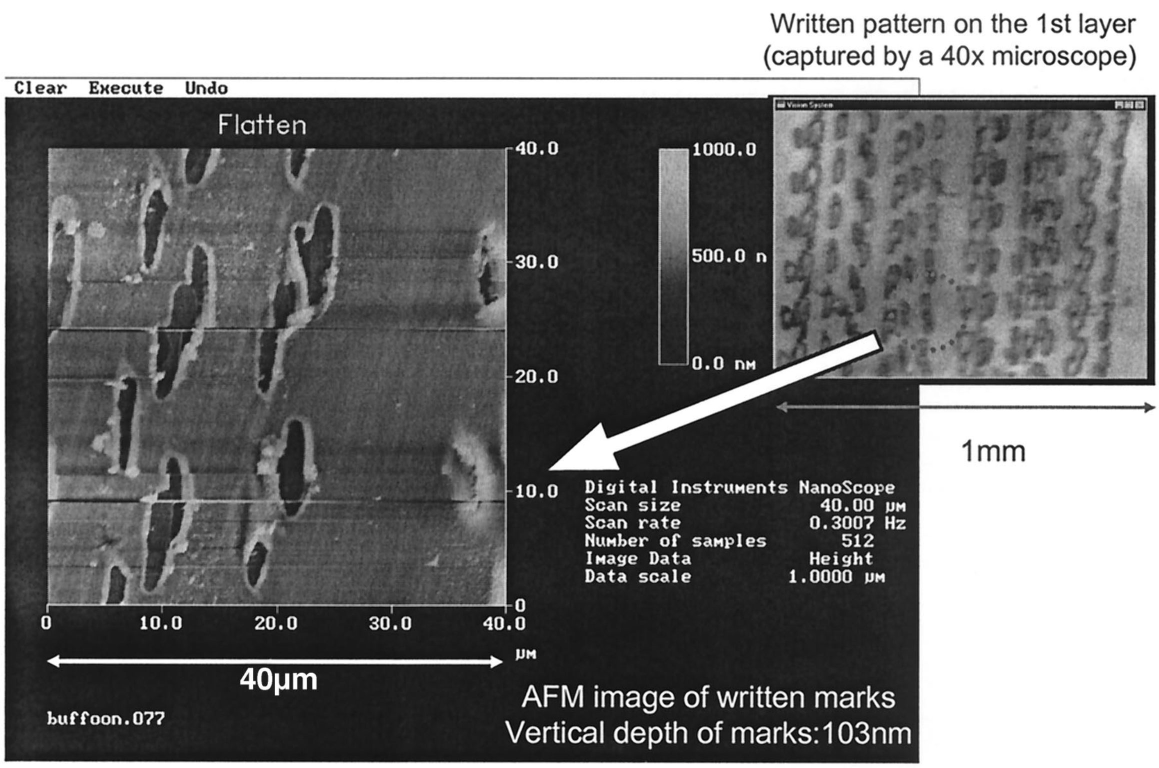

Fig. 8. AFM image of the written marks on the first recording layer. The vertical depth of the written marks is ~103 nm.

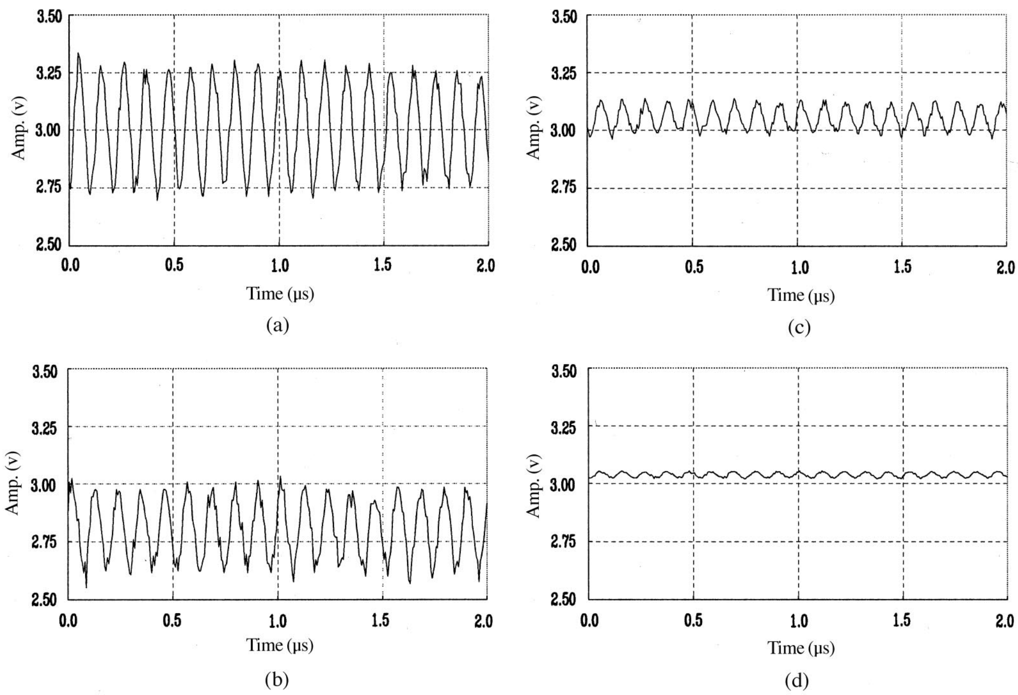

Fig. 10. Readout signals from recording layers (a) 1, (b) 2, (c) 3, and (d) 4.

References and Notes

1. B.-W. Yang and H.-P. D. Shieh, "Interlayer cross talk in dual-layer read-only optical disks," Appl. Opt. **38,** 333–338 (1999).
2. F.-H. Wu and H.-P. D. Shieh, "Thermochromism of silver oxide for optical switching layers in volumetric optical disks," Jpn. J. Appl. Phys. **42,** 820–823 (2003).
3. F.-H. Wu and H.-P. D. Shieh, "Optical switching layer for re-writable volumetric optical disks," Jpn. J. Appl. Phys. **41,** 1683–1684 (2002).
4. F.-H. Wu, H.-P. D. Shieh, T. D. Milster, and D.-R. Huang, "Write-once volumetric optical disk using transparent recording material with an optical switching layer," Jpn. J. Appl. Phys. (to be published).
5. J. Tominaga, H. Fuji, A. Sato, T. Nakano, and N. Atoda, "The characteristics and the potential of super resolution near-field structure," Jpn. J. Appl. Phys. **39,** 957–961 (2000).
6. R. E. Gerber, M. Mansurupur, and J. M. Sasian, "Versatile objective lens with adjustable correction for different wavelengths and substrate thicknesses for testing optical disks," Appl. Opt. **36,** 2414–2420 (1997).
7. Diffract software from MM Research, Inc., 5748 North Camino del Conde, Tucson, Ariz. 85718.