Superresolution optical disk with a thermoreversible organic thin film

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Recording and retrieving small marks far beyond the optical diffraction limit in a high-speed rotating phase-change optical disk have been investigated by use of a thermoreversible organic thin film as a superresolution mask layer. The organic thin film exhibited significant thermoreversibility and rapid response on laser irradiation. Recorded marks as small as 120 nm in length could be detected by a dynamic disk tester with a laser wavelength of 635 nm and a numerical aperture of 0.6. © 2001 Optical Society of America

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To meet the requirement of growing demands for information processing, continuing efforts have been devoted to increasing the recording density in optical and magnetic data storage. In the optical data storage system described here, the areal storage density is determined by a spot size (full width at half-maximum) of a focused laser beam, which is generally limited by the diffraction of light. In a conventional optical system with a laser wavelength of 635 nm and a N.A. of 0.6, the minimum mark period in a single-tone pattern that can be detected is approximately 530 nm. If the duty cycle is 50%, the minimum detectable mark length is approximately 265 nm. Various approaches to increasing recording density, of which the superresolution technique is one of the most feasible, have been proposed.[1] The search for high-performance mask layers including organic materials for increasing the carrier-to-noise ratio (CNR) continues to be an urgent task.[2,3]

In this study, an organic material with pronounced thermoreversibility is applied in a phase-change optical disk as a superresolution mask layer. The thermoreversible thin film exhibits significant change in its optical properties as the temperature increases. Recording and retrieving signals of marks smaller than the diffraction limit are investigated and confirmed through the use of a mask layer with a high-speed disk rotation.

Figure 1 depicts the multilayers of a phase-change optical disk with a thermoreversible thin film as a mask layer. A glass disk of 0.6-mm thickness and 12-cm diameter was used as a substrate. The thermoreversible organic thin film was prepared upon the substrate by spin coating at a rotation speed of 3000 rpm. The film consists of 2-N,N-dimethylamino-6-diethylaminofluoran as a color former and an aromatic derivative of $4,4'$-ethylidenediphenol as a color developer in a molar ratio of 1:1. The mask layer and the Ge$_2$Sb$_2$Te$_5$ recording film were separated by a 40-nm-thick ZnS–SiO$_2$ layer. To prevent oxidation and heat shock, we covered the recording film with another ZnS–SiO$_2$ layer (20 nm). The Ge$_2$Sb$_2$Te$_5$ and ZnS–SiO$_2$ (0.8:0.2 atomic ratio) films were deposited consecutively by rf magnetron sputtering without breaking the vacuum. The recording and retrieving signals were measured by an optical disk drive tester (DDU-1000, Pulstec Industrial Co., Ltd.) with a wavelength of 635 nm and a N.A. of 0.6.

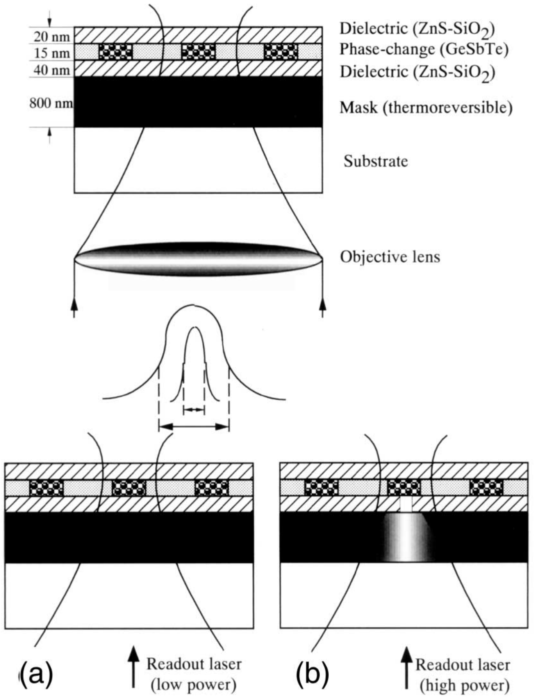

Fig. 1. Schematic illustration of the superresolution effect with a thermoreversible mask layer and low high reading power.

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Measured by a microheating stage, a mask layer that has been spin coated onto a glass substrate shows a drastic change in transmittance as the temperature increases or decreases. In Fig. 2 the solid and dotted curves indicate heating and cooling processes, respectively, for an 800-nm-thick thin film. The change is initially small, but it becomes remarkable at a temperature higher than 370 K, and the change is mostly reversible by a change in temperature. Because of absorption at a wavelength near 635 nm, the temperature of the thin film will be elevated locally on laser irradiation, and the result will be an increase in the transmittance of the thin film.

The applicability of the layer as a mask may be evaluated by use of *ABC* parameters[4]:

$$A = \frac{1}{d}\ln[T(\infty)/T(0)], \tag{1}$$

$$B = -\frac{1}{d}\ln[T(\infty)], \tag{2}$$

$$C = \frac{A + B}{AI_0 T(0)[1 - T(0)]}\,\frac{\mathrm{d}T}{\mathrm{d}t}, \tag{3}$$

where d is the thickness of the thermoreversible thin film, $T(0)$ is an initial transmittance before exposure to light, $T(\infty)$ is a saturated transmittance of the film after complete exposure to light, and I_0 is the intensity of light just in front of the film. For the maximum superresolution effect, the transmittance change between $T(\infty)$ and $T(0)$ must be as large as possible. With regard to *ABC* parameters, a large A parameter and a small B parameter are required. For the film used in this study, the values of parameters A and B can be estimated to be 1.3 and 0.1, respectively. Time response factor $\mathrm{d}T/\mathrm{d}t$ is also important in increasing parameter C, because faster switching can further increase the data transfer rate. For the transmittance of the thermoreversible thin film (800 nm) measured by a pump–probe technique with a nanosecond pulse laser at 532 nm and an acousto-optically modulated microsecond-pulsed He–Ne laser (633 nm) as the pump and the probe beams, respectively, the rise time will be ~20 ns on laser irradiation, and the transmittance of the thin film will be recoverable with a recovery time of ~800 ns.

Figure 3 shows the reading-power dependence of the reflectance and transmittance of the sample optical disk as measured by the disk drive tester. First, the reflectance and transmittance increase linearly at a reading power of less than 2.0 mW, and then small plateaus appear at 2.0–2.5 mW. It is thought that in this region the laser energy is absorbed in the film and used for accomplishing the molecular change. That is, the power will correspond to the threshold temperature (370 K) in Fig. 2. As the temperature increases further, the transmittance and reflectance gradually increase again, because of the unmasking of the phase change layers. Figure 4 shows an illustration of the superresolution. The initial state of the as-deposited thermoreversible thin film with low transmittance shades all the recorded marks. As the power increases, the film absorbs light to produce heat and then reaches the threshold temperature. A small discolored area is generated as the power increases further. This window works as a superresolution aperture.

Figure 5 shows the relationship between CNR and the reading laser power of the disk. Mark trains with mark lengths of 200 nm were recorded on the disk by the disk drive tester with a laser power of 14.0 mW

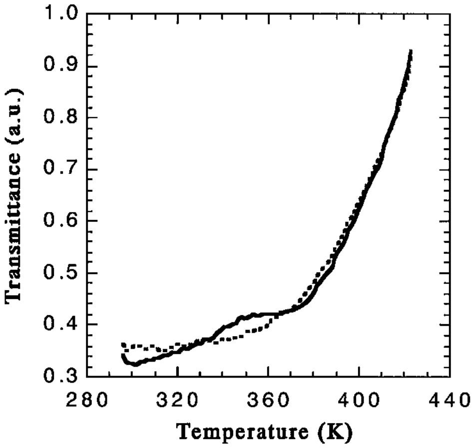

Fig. 2. Temperature dependence of the transmittance of the thermoreversible thin film (800 nm) at a wavelength of 635 nm during heating and cooling: solid curve, heating; dotted curve, cooling.

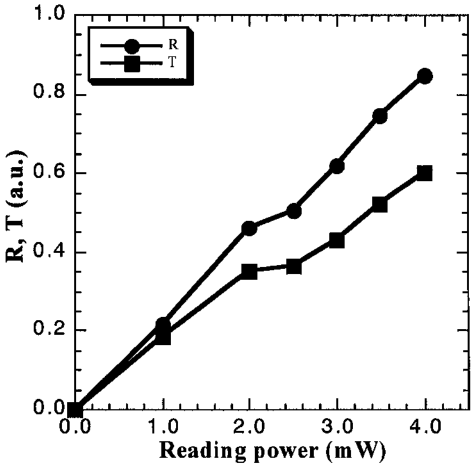

Fig. 3. Reading-power dependence of the reflectance (R) and the transmittance (T) of the disk.

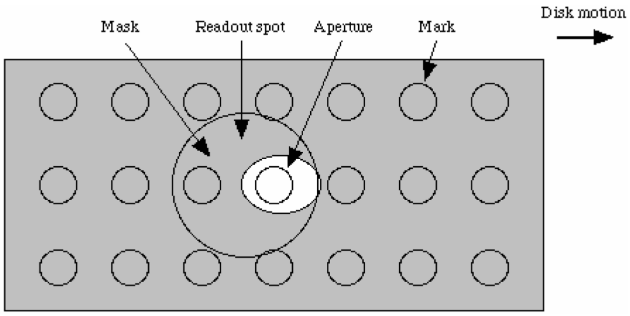

Fig. 4. Illustration of superresolution with a thermoreversible organic thin film as a mask layer.

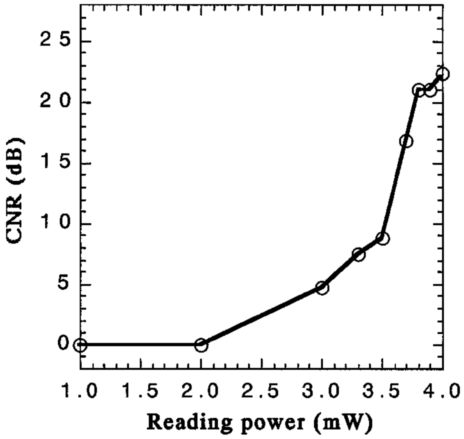

Fig. 5. Relationship between CNR and reading power at a CLV of 6.0 m/s. The mark length and the recording power were set to be 200 nm and 14.0 mW, respectively.

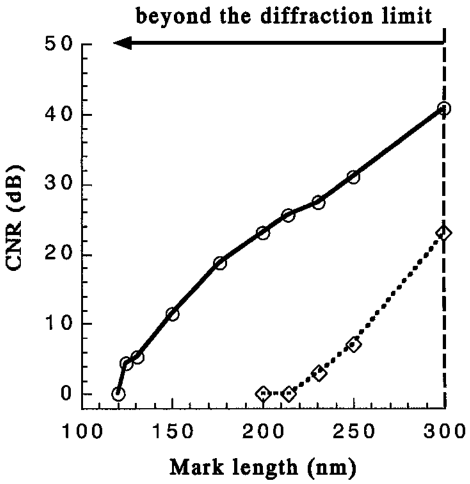

Fig. 6. Relationship between CNR and mark length for a recording power of 14.0 mW at a CLV of 6.0 m/s. The reading powers were 4.0 mW (circles) and 1.0 mW (diamonds).

at a constant linear velocity (CLV) of 6.0 m/s. This mark length cannot be detected by this optical pickup because of the diffraction limit. A signal readout was also made at the same CLV. It is clear that the CNR indicates a strong dependence on the reading power in the superresolution readout. The value of the CNR is small at low reading power but rapidly increases at higher reading power; it reaches ~22 dB at a reading power of ~4.0 mW. Relatively small signals appear in the power range of 2.0–3.0 mW, which seems to correspond to the plateaus shown in Fig. 3. The resolution potential of the disk is shown in Fig. 6. When a low reading power (1.0 mW) is applied, the signal disappears at less than 300 nm, which agrees with the theoretical diffraction limit of the optical pickup. However, small marks, of as little as 120 nm, could be detected by the superresolution effect, depending on the organic discoloring reaction.

In summary, a thermoreversible thin film was used as a superresolution mask layer in an optical disk. The superresolution effect was generated by the optical discoloring response of the organic mask layer in the multilayer structure. Recorded marks as small as 120 nm could be detected in a phase-change optical disk mounted upon a dynamic disk tester with a laser wavelength of 635 nm and a N.A. of 0.6. One could improve the CNR by overcoming the limiting factors, such as small A and large B parameters, or spectroscopically. The resolution limit of this technique could be further reduced if a shorter-wavelength diode laser and a higher-N.A. lens were used in the optical pickup system. Compared with the superresolution near-field structure that uses inorganic materials such as Sb and AgOx,[5,6] an organic mask layer with thermoreversibility presents a unique approach to retrieving small marks that has the merits of large variety, low cost, and the potential to be applied in many fields.

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