Readout of super-resolution marks with Ti thin film

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Using Ti as the super-resolution reflective film to replace the Al reflective layer in conventional read-only optical disk, the recording marks with a diameter of 380 nm and a depth of 50 nm are read out in a dynamic testing device whose laser wavelength is 632.8 nm and numerical aperture of the lens is 0.40. The optimum Ti thin film thickness is 18 nm and the corresponding signal-noise-ratio is 32 dB.
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Super-high density optical storage has been very attractive for high definition television system and computer network servers, which requires the recording marks to be smaller than the optical diffraction limit. Using a disk drive for recordable digital-versatile-disk and an optical phase-change layer, marks with different size can be thermally recorded which are beyond the diffraction limit because the formation of the marks in the phase-change layer does not depend on the spot size, but on the heat gradient supplied by the laser[1]. Carefully tuning the laser power and velocity of the optical disk motion means that, in principle, marks with a size of less than 100 nm can be achieved. Tominaga *et al.* recorded the smallest marks of $80-100$ nm by super-resolution near-field structure whose mechanism can be explained by a thermal lens model[2−7]. For readout, the marks must be detected by the reflectance change between the recorded and the nonrecorded regions, however, due to the marks being smaller than the spot, there will exist lots of marks within a readout spot, and they cannot be read out, thus the readout of super-resolution marks is very significant and interesting. Yasuda *et al.* first realized the readout of super-resolution marks in read-only optical disk[8], subsequently, they optimized the optical disk structure and demonstrated the feasibility of increasing both the linear density and the track density of optical disk[9]. Wu *et al.* theoretically proposed and investigated into a kind of double mask layer read-only optical disk structure to realize the readout of super-resolution marks[10]. However, the optical disk structures mentioned above are very complicated, the readout signal is sensitive to the thin film thickness and homogeneity of different layer. The process is also more complicated than that of the conventional read-only optical disks and the fabrication cost is higher. In order to overcome these disadvantages, Kikukawa and Wei *et al.* proposed to use the thin film with nonlinear optical property as a super-resolution reflective film (SRRF) to replace the Al reflective layer in conventional read-only optical disk and realized the readout of super-resolution marks[11−17]. In this letter, we propose to use Ti as the SRRF to replace the Al reflective layer in read-only optical disk and obtain the good experimental results.

The optical disk structure is shown in Fig. 1, where Ti and Al thin films are used as the reflective layer, respectively. The SiN thin film is used as a protection layer. The polycarbonate substrates with diameter of 120 mm and thickness of 1.2 mm are used, where the recording pit depth is about 50 nm and pit (space) diameter is 380 nm (shown in Ref. [12]). The Ti and Al thin films were deposited by RF sputtering at the background pressure of less than 1.0×10^{-4} Pa. The SiN thin film was deposited by a reactive sputtering technique with a Si target by introducing a gas mixture of Ar and N_2, the ratio of N_2 to the total gas mixture pressure was fixed at 15%. The SiN thin film thickness in our experiment was fixed at 50 nm, and its refractive index is evaluated as $2.15+0.02i$ at the wavelength λ of 632.8 nm. The readout of recording pits was carried out using a dynamic testing device (shown in Ref. [12]) with a wavelength of 632.8 nm and with a numerical aperture (NA) of a lens at 0.40. Generally, the resolution limit of optical readout is given as $\lambda/4$ NA, thus the resolution limit of the device is about 400 nm. In the experiment, the readout velocity was fixed at 6 m/s and the readout power was varied and optimized.

In order to confirm the spatial resolution of the dynamic testing device, the optical disks with a structure in Fig. 1(a) are measured, the results are shown in Fig. 2, it is seen that the recording pits cannot be read out. Then the optical disks with a structure in Fig. 1(b) are also measured and the results are given in Fig. 3. The recording pits can be read out and the signal-noise-ratio (SNR) is 32 dB. At the same time, the oscilloscopic signal

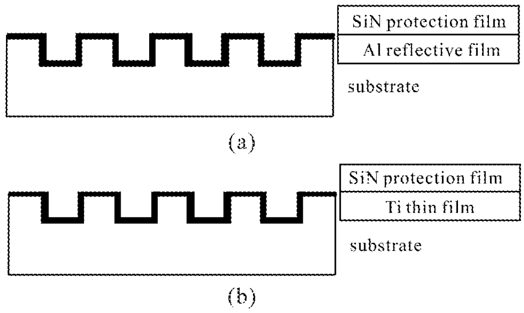

Fig. 1. Optical disk structure. (a) Conventional read-only optical disk; (b) super-resolution optical disk.

is regularly modulated by the recording pits. By analyzing the optical disk structure shown in Fig. 1, in the conventional readout, there are two or more recording pits in a readout spot (shown in Ref. [12]), the recording pits cannot be read out because the spatial frequency is higher than 4 NA/λ, as shown in Fig. 2. Using the Ti thin film to replace the Al reflective layer, during the signal reproduction, because of the Gaussian distribution of the laser beam energy and optical disk motion, the laser energy is absorbed and transferred into heat energy by the thin film, and the temperature rise at the rear portion of the spot is higher than that at the front portion. When the temperature exceeds the melting temperature, the solid Ti thin film will change to melted state. At the front portion of the spot, Ti is still in solid state (shown in Ref. [12]). Because the complex refractive index of Ti thin film in solid and melted states is different, the reflectance and transmittance are also different, which make one part of the spot be masked and the other reflected by the Ti thin film. Therefore, for the readout of super-resolution optical disks, the Ti thin film functions as both a mask and a reflective layer. These can be described as follows. In the course of readout, the readout spot with an electric field distribution $E_0(r)$ (shown in Fig. 4) is projected onto the SRRF, let the SRRF function be $O(r)$ and its amplitude transmittance be $t(r)\cdot O(r)$, where $t(r)$ is nonlinear transmittance according to[18]

$$t(r) = t_0[1 + \chi \cdot g(E_0)], \tag{1}$$

where $g(E_0)$ represents the dependence on the readout light, and the nonlinearity of the SRRF is characterized by χ. Immediately after the SRRF, the transmitted field can be written as

$$E_{t,0}(r) = E_t(r) \cdot O(r), \tag{2}$$

$$E_t(r) = t(r) \cdot E_0(r). \tag{3}$$

Signal from the SRRF may be found from the Fourier transform of $E_{t,0}(r)$. We integrate the signal over a detection pupil $P(\rho)$, which corresponds to the same NA as the spot-forming pupil. Resolution can easily be judged with the aid of the frequency response function $R(f)$. Since consider spatial frequency, the SRRF is taken to be a grating with discrete orders. In the case of gratings covered with a nonlinear layer, the spot narrowing yields an aperture widening after passing. Widely opened diffracted beams overlap the detection pupil up to larger diffraction angles, thus interference between zero and first orders possibly reaches higher spatial frequency. Since only the detected region has to be taken into account, the response $R(f)$ is given by the convolution of the field $\tilde{E}_t(\rho)$ in the detection pupil with the field itself,

$$R(f) \propto |[\tilde{E}_t(\rho) \cdot P(\rho)] \otimes \tilde{E}_t(\rho)|, \tag{4}$$

where $\tilde{E}_t(\rho)$ is the Fourier transform of $E_t(r)$. Let $G(\rho)$ represent the Fourier transform of g with respect to r. Then Eqs. (1) and (3) lead to

$$\tilde{E}_t(\rho) = t_0[\tilde{E}_0(\rho) + \chi G(\rho) \otimes \tilde{E}_0(\rho)], \tag{5}$$

where $\tilde{E}_0(\rho)$ corresponds to the conventional linear case, with Eq. (4) it yields the customary incoherent modulation transfer function. $\chi G(\rho) \otimes \tilde{E}_0(\rho)$ shows the influence of the nonlinearity. Because the convolution covers a wider field than $\tilde{E}_0(\rho)$, the nonlinear part of $\tilde{E}_t(\rho)$ will extend beyond the value NA/λ. This is the beam widening due to the spot narrowing. From Eq. (4) it then follows that $R(f)$ will show a finite value above the conventional f_c, there will be super-resolution. Therefore, the super-resolution pits can be dynamically read out by the nonlinear Ti thin film.

In addition, Fig. 5 shows the SNR dependence on the Ti thin film thickness, the SNR increases with thin film thickness. When the thickness reaches 18 nm, the SNR reaches the maximum (32 dB), and then decreases, which may be due to the thin film thickness changing its homogeneity and contrast of reflectance and transmittance between solid and melted state.

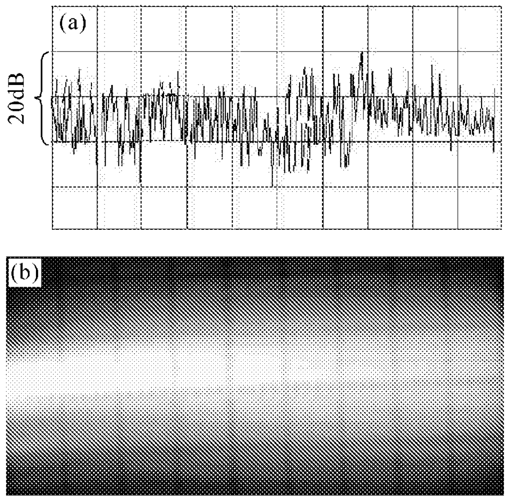

Fig. 2. Dynamic measuring results of optical disk with Al reflective layer. (a) Frequency-spectrum signal; (b) oscilloscopic signal modulated by recording marks.

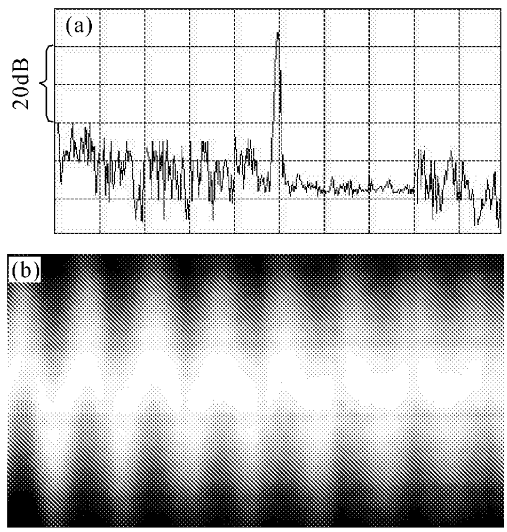

Fig. 3. Dynamic measuring results of optical disk with Ti super-resolution reflective film. (a) Frequency-spectrum signal; (b) oscilloscopic signal modulated by recording marks.

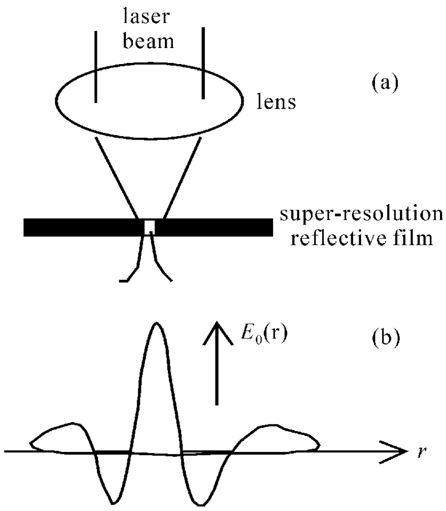

Fig. 4. Principle of super-resolution. (a) Super-resolution reflective film irradiated by laser beam; (b) electric field distribution.

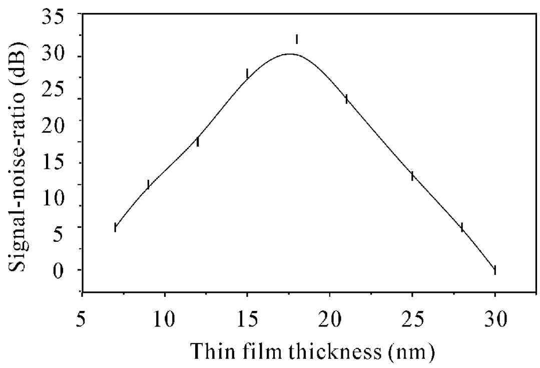

Fig. 5. SNR dependence on the thin film thickness.

In conclusion, we use Ti as the SRRF and realize the dynamic readout of super-resolution pits in conventional read-only optical disk, the optimum Ti thin film thickness is 18 nm and the SNR is 32 dB.

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