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Erasable Phase Change Disks with Super Resolution Capability by Pulse-Readout

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Erasable thermal phase change super resolution (EPSR) disks composed of mask and recording layers can be fabricated with a "below-diffraction-limited" aperture within the readout spot to achieve optical super resolution. The formation of the aperture and the readout signal on the EPSR disk were analyzed. The feasibility of the designed EPSR disks was evaluated by thermal simulation. A carrier-to-noise-ratio (CNR) of 32 dB at mark size of 0.4 μm, 8 dB higher than that in a conventional disk, was obtained by applying pulse-readout to the EPSR disks at a wavelength of 780 nm and numerical aperture of 0.55.

KEYWORDS: erasable thermal phase change super resolution disk (EPSR), optical super resolution, mask layer, recording layer, below-diffraction-limited aperture, pulse-readout

In optical disk storage devices, the recording density is restricted by the law of diffraction and is about 0.6 λ/NA, where λ and NA are the laser wavelength and numerical aperture of the objective lens, respectively. Although the use of short wavelength laser diode and high NA lens can increase the recording density, the blue laser diode and lens with NA higher than 0.6 are still costly expensive and not quite readily available.

The diffraction-limitation can be circumvented by applying a super-resolution technique, i.e., the formation of an equivalent readout aperture within a diffraction-limited reading spot; thus, the recording density can be greatly increased at the given laser wavelength and objective NA. The magnetic super resolution (MSR)[1] method has already been applied to erasable magneto-optical (MO) recording to increase the capacity of 3.5″ disks up to 7 GByte.[2] However, the super-resolution technique using phase change media was reported only for the case of read-only disks.[3]

This letter reports the successful demonstration of a super-resolution technique on erasable phase change disks. The readout signals of erasable phase change super resolution (EPSR) disks were analyzed by optical simulation; the feasibility of the effective detection of marks on EPSR disks was evaluated by thermal analyses. Using the pulse-readout technique,[4] below-diffraction-limited marks can be detected with adequate carrier-to-noise-ratio (CNR).

The mechanism of below-diffraction-limited mark detection in an EPSR disk is ascribed to the refraction index of the phase change material as a function of temperature. When the temperature of the phase change material is above the melting temperature T_m, the index of refraction, both real (n) and imaginary (k) parts, decrease rapidly. By using sharp temperature variations on n and k, optical super resolution can be achieved.

The EPSR disk is composed of a mask layer, and a recording layer as the active layer; both layers were composed of phase change medium GeTeSb, but with different ratios of contents, therefore, with different critical cooling rates, as shown in Fig. 1. Three dielectric layers, top, middle, and bottom, are all composed of ZnS–SiO_2. The functions of the middle dielectric layer were to prevent the diffusion of material between the mask and recording layers, and to control the cooling rate of the mask layer. The top and bottom dielectric layers were used to control the reflection coefficient of the EPSR disk and the cooling rate of the recording layer, respectively. The aluminum (Al) layer functioned as a heat sink and as a reflective layer.

The detection of below-diffraction-limited marks on the EPSR disks is to yield the difference between the refraction indices of the mask layer near melting temperature. The amorphous marks and crystalline unrecorded area of the recording layer correspond to two different refraction indices. When the light spot scans the readout track, the temperatures of the rear and front parts of the mask layer in the light spot are above and below the melting point T_m, respectively, which also correspond to two different refraction indices, as shown in Fig. 1(a). Therefore, four reflection coefficients, R_{ma}, R_{mx}, R_{sa}, R_{sx}, exist within a diffraction-limit light spot, as shown in Fig. 1(b). In the melting region of the mask layer, R_{ma} and R_{mx} denote the reflection coefficients when the recording layer is in the amorphous and crystalline state, respectively; while in the solid region of the mask layer, R_{sa} and R_{sx} denote the reflection coefficients when the recording layer is in the amorphous and crystalline state, respectively.

When using rear aperture detection (RAD), the reflection coefficients, R_{ma} and R_{mx}, and the contrast ratio, $(R_{mx}$ −

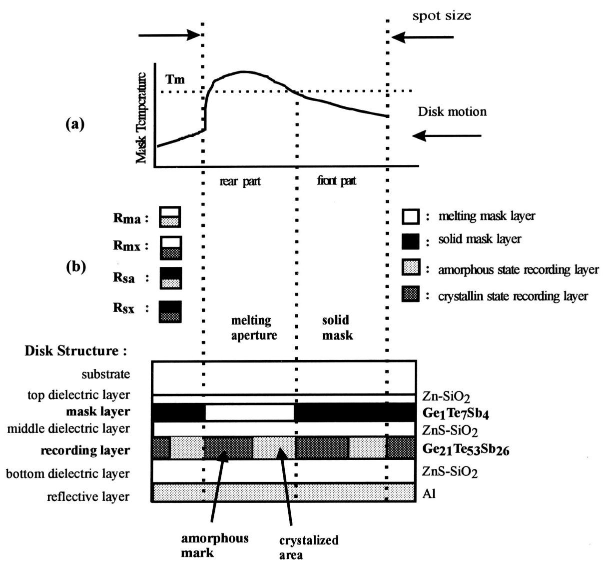


Fig. 1. (a) Temperature profile in the mask layer. T_m is the melting point of the mask layer. (b) Disk structure and detection of the EPSR disk. R_{ma}, R_{mx}, R_{sa}, and R_{sx} denote the reflection coefficients within a diffraction-limited light spot.

$R_{ma})/R_{mx}$, within the melting aperture should be designed higher than those in the solid mask area. As a result, the contrast ratio within the melting aperture area mainly determines the signal modulation of the reading spot; in contrast, $(R_{sx} - R_{sa})/R_{sx}$ in the solid mask area results in noise during readout.

At a wavelength of 650 nm and NA of 0.6, the full-width at half maximum (0.6 λ/NA) of the light spot was about 0.64 μm. The mark size and the spatial frequency of the recorded pit employed in the simulation were 0.25(0.6 λ/NA) or 0.16 μm, and 0.5(0.6 λ/NA) or 0.32 μm, respectively; in other words, a light spot covered two pit periods. Reflection-coefficient profiles of RAD are shown in Fig. 2, where R_{ma}, R_{mx}, R_{sa}, and R_{sx} are 0.154, 0.270, 0.143, and 0.158, respectively. Therefore, the contrast ratio $(R_{mx} - R_{ma})/R_{mx}$ of 43% in the aperture region was much higher than the contrast ratio $(R_{sx} - R_{sa})/R_{sx}$ of 9.5% in the mask region; thus, the detection of below-diffraction-limited marks in the EPSR disks becomes possible.

The feasibility of the optically designed EPSR disk was then evaluated by thermal simulation. In the reading analysis on EPSR disks, the allocation of laser energy within the disk structure was simulated by the thin-film theorem and heat diffusion equations.[5] The discrete temperature profile was derived by the alternative direction implicit technique of the finite difference method, where the mesh sizes of time and space were 1 ns and 2 nm, respectively; the properties of multi-layer thin-film materials adopted in the calculation are shown in Table I.[3,6] The simulation results obtained using

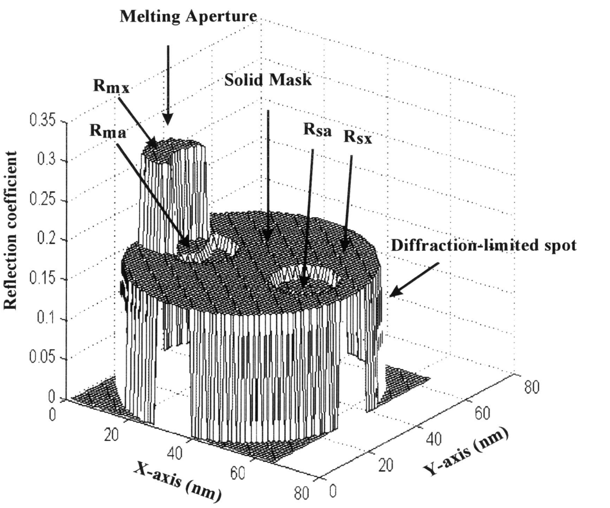


Fig. 2. Reflection-coefficient profiles of RAD. Mark size and light-spot size are 0.16 μm and 0.64 μm, respectively. R_{ma}, R_{mx}, R_{sa}, and R_{sx} are 0.154, 0.270, 0.143, and 0.158, respectively.

Table I. Thermal properties of EPSR disk layers used for calculations.[6]

Thin-film materials	Thermal conductivity ($J\,cm^{-1}\,K^{-1}\,s^{-1}$)	Specific heat ($J\,cm^{-3}\,K^{-1}$)
ZnS–SiO_2	0.0658	2.044
$Ge_1Te_7Sb_4$	0.0058	1.285
$Ge_{21}Te_{53}Sb_{26}$	0.0058	1.292
Al	2.144	2.448

DC laser beam scanning along a track of the EPSR disk revealed that the wall width of the readout aperture in the mask layer was too thick due to the heat diffusion, to yield adequate CNR. Moreover, when the temperature of the mask layer of the recording layer was above the melting temperature T_m at a read power of 5.5 mW, the temperature of the recording layer exceeded the crystallization temperature T_x, shown in Fig. 3; thus, the amorphous marks in the recording layer were erased. Alternatively, the adopting of pulse-readout could result in the formation of an melting aperture with a thinner aperture wall and prevent the erasing of amorphous marks in the recording layer by reducing the heat transmitted into the disk. Thus, the pulse-readout method was adopted to obtain a readout of below-diffraction-limited marks on the EPSR disks.

A conventional four-layer erasable phase change disk was tested at a wavelength of 780 nm and NA of 0.55; thus, the full-width at half maximum was 0.85 μm. The measured CNR at a writing frequency of 3 MHz and linear velocity of 5 m/s was 55 dB, corresponding to a mark size of 0.83 μm; however, CNR reduced to 23 dB at a writing frequency of 7 MHz, corresponding to a below-diffraction-limited mark size of 0.4 μm.

An EPSR disk designed to meet the optical and thermal requirements was measured using a dynamic disk tester with a wavelength of 780 nm and NA of 0.55 under the same testing conditions as those used for the conventional disks. The formation of the melting readout aperture was analyzed by employing a reading pulse of 14 MHz, double of the signal frequency on the tested track, to avoid confusion between the signal frequency (7 MHz) and the reading pulse frequency (14 MHz). The width and high/low power level of the reading pulse were 50 ns and 6 mW/2 mW, respectively.

On application of fast fourier transform (FFT) to the readout signal measured by a digital oscilloscope, two peaks appeared on the power spectrum of the EPSR disks: One was the signal frequency of 7 MHz on the recording layer, the other was the laser pulse frequency of 14 MHz, as shown in Figs. 4(a) and 4(b), respectively. The CNR obtained by mea-

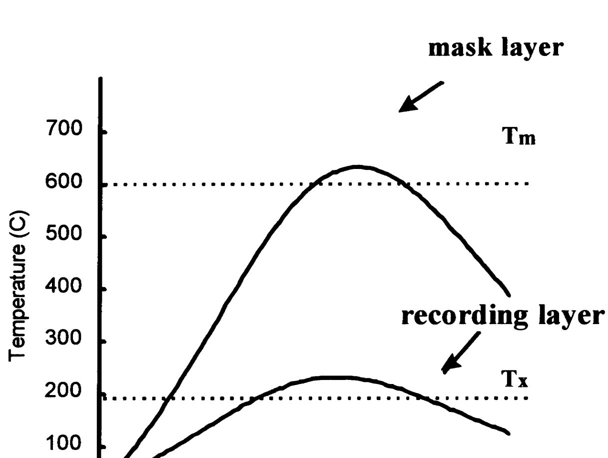
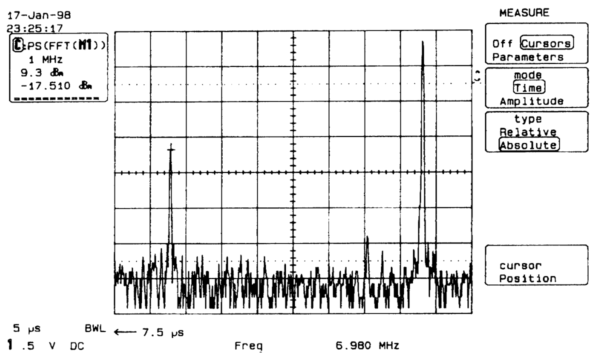
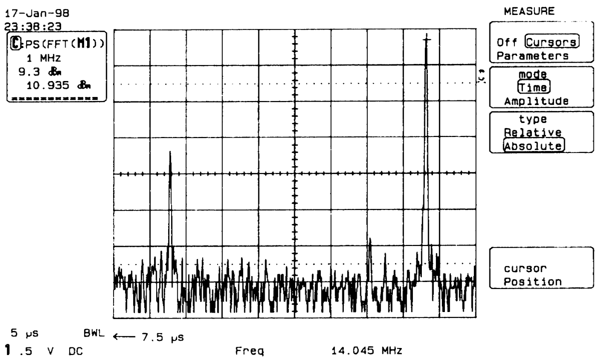


Fig. 3. Temperature profiles on the recording and mask layers of the EPSR disk at DC-read detection. T_m and T_x are the melting and crystallized temperature, respectively. Read power and linear speed are 5.5 mW and 5 m/s, respectively.



(a)



(b)

Fig. 4. FFT of the signal measured by applying pulse-readout to the EPSR disks. The measuring marker at signal frequency of (a) 7 MHz (b) 14 MHz.

suring the below-diffraction-limited mark size of 0.4 μm on the EPSR disks by pulse-readout was 32 dB, 8 dB higher than the CNR in the conventional single-recording-layer phase change disk, as shown in Fig. 5.

From the difference between the measured CNR of a conventional four-layer disk and a six-layer EPSR disk, a thermal readout aperture was successfully demonstrated to form on the mask layer of the EPSR disks to detect "below-diffraction-limited" marks. The results were in agreement with those obtained by both optical and thermal analyses. The minimum detectable mark size on the EPSR disk was 0.25(0.6 λ/NA) by pulse-readout. When using a laser wavelength of 780 nm and an NA of 0.55, the detectable minimum mark size on the EPSR disk reduced to 0.21 μm, i.e., pit length of 0.42 μm, which was the same as the minimum pit length of the DVD-

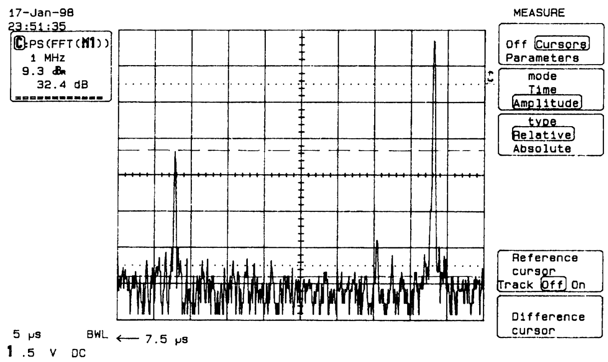


Fig. 5. CNR of 32 dB measured at a mark size of 0.4 μm on the EPSR disks using the pulse-readout.

ROM disk of 4.7 GByte using a laser wavelength of 650 nm and an NA of 0.6. If 650 nm wavelength and 0.6NA were used in reading the EPSR disks, the capacity could increase by 1.6 times, i.e. 7.52 GByte in an EPSR disk; therefore, the recording capacity of the erasable phase change disk could be considerably increased.

An erasable phase change disk consisting of mask and recording layers of different phase change materials with different critical cooling rates, in which the formation of a below-diffraction-limited aperture for readout could be achieved, was demonstrated. To a form sharp temperature gradient on the mask layer of the EPSR disk without erasing amorphous marks on the recording layer, pulse-laser reading was used to form a well-defined sub-μm detecting aperture. Using a laser wavelength of 780 nm and objective lens of 0.55NA, CNR of 32 dB was obtained at a mark size of 0.4 μm on the EPSR disk by pulse-readout, 8 dB higher than that in the conventional disk. Optimization of layer materials and layer structure is being studied for super-resolution readout to further increase the density, and thus the capacity of erasable phase change disks.

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