RECENT PROGRESS IN MAGNETICALLY INDUCED SUPERRESOLUTION

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Abstract—Progress in Magnetically induced SuperResolution since first reported in 1991 is reviewed. Recording on the disk by front aperture detection (FAD) was achieved for a bit length of 0.27 μm both by light intensity modulation and by magnetic field modulation. Since rear aperture detection (RAD) has the advantage of reducing crosstalk, the RAD type has the promise of realizing the huge capacity MO disk. RAD by a small initializing field and RAD by magneto-static coupling are expected to allow track pitches as narrow as 0.7 μm and bit lengths the same as achieved by FAD.

INTRODUCTION

The huge capacity optical disk has been demanded for multimedia and digital video applications. The recent increase in areal density is shown in Fig. 1. Since 1988 when magneto-optical disks were standardized, the capacity of the MO disk has been continually increased for data use. Most recently disks with 1.3 GB/130 mm side (4x) and 640 MB/86 mm side (5x) were put into the market in 1995. The MO drive named HS which is overwritable by magnetic field modulation was also commercialized with 650 MB/88 mm side. The 130 mm disk with 8x capacity is now being standardized by the ISO. Various technologies such as zoning, short wavelength recording, partial response maximum likelihood (PRML), writing compensation, crosstalk cancellation, and land/groove recording have been proposed to increase the areal density further in the phase change disk and the magneto-optical disk.

The rewritable DVD standard will be a phase change disk with 2.6 GB/120 mm side using land/groove recording[1], while the DVD-ROM standard will specify a capacity of 4.7 GB/120 mm side and will be commercialized in 1996. Meanwhile, a higher density of 5 GB/120 mm has already been reported by land/groove recording on a phase change disk [2].

Land/groove recording on the magneto-optical disk was also investigated by using PRML [3] and by adjusting the groove depth and Kerr ellipticity of the MO disk [4]. Although the phase change disk has been much improved, the magneto-optical disk still has some advantages.

1. MO disk reliability for repeated writing is more than one million times which is required for data application.
2. A wider recording power margin is obtained by magnetic field modulation recording because mark edges are not affected by variations in recording power.
3. Magnetically induced SuperResolution (MSR) which is unique to the magneto-optical disk can possibly increase the areal density substantially.

Thus, we believe the magneto-optical disk currently holds most promise for increasing capacities especially for data use. In this paper we will concentrate on recent progress in MSR and the prospect of incorporating MSR into huge capacity magneto-optical disks in the near future.

EVOLUTIONARY TREE OF MSR

Figure 2 shows the evolutionary tree of MSR with the rare earth-transition metal amorphous material as the original ancestor. Since the performance characteristics of TbFeCo exhibit a good balance between moderate carrier levels and low noise, it still prevails in current magneto-optical disks. The exchange-coupled magnetic multilayers proposed in 1981[5] resulted in applications such as double layer films for high carrier levels[6], multilayer films for direct overwriting by light intensity modulation[7], and multilayer films for MSR. Two detection methods, front aperture detection (FAD) and rear aperture detection (RAD), were proposed for MSR in 1991[8]. Figure 3 shows the disk structure commonly found among the various types of MSR reported since then. Marks are recorded on the recording layer and the information in the readout layer is read out by superresolution. The intermediate layer can be a magnetic layer like TbFe, or a dielectric layer like SiN, or even absent according to the type of MSR.

In FAD, the heated region towards the rear of the light spot is optically masked by the exchange-coupled magnetic triple layers and the signal is detected from the remaining aperture at the front of the light spot as shown in Fig. 4a. The achievement of superresolution was indicated by a high C/N ratio of 45 dB obtained at the optical limit. A new method was
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**Fig. 2. Evolutionary tree of MSR**

- **1980**
  - RE-TM amorphous GdCo
  - TbFeCo
  - Exchange-coupled multilayer
  - Overwrite by light intensity modulation

- **1990**
  - High carrier level
  - MSR
  - FAD [8]
  - Magneto-static coupled
    - R-MSR [9]

- **1995**
  - RAD [8]
  - No initializing field
    - (CAD) [11]
  - Small initializing field [10]
  - Double masked [12]

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**Fig. 4. Two detection method for MSR.**

(a) FAD

- Light spot
- Masked area
- Disk motion

(b) RAD

- Light spot
- Masked area
- Disk motion

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**Fig. 3. The disk structure which is common for MSR.**

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Poly-carbonate</th>
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<tbody>
<tr>
<td>Dielectric layer</td>
<td>Si$_3$N$_4$</td>
</tr>
<tr>
<td>Readout layer</td>
<td>GdFeCo 30-50 nm</td>
</tr>
<tr>
<td>Intermediate layer</td>
<td></td>
</tr>
<tr>
<td>Recording layer</td>
<td>TbFeCo 30-50 nm</td>
</tr>
<tr>
<td>Dielectric layer</td>
<td>Si$_3$N$_4$</td>
</tr>
<tr>
<td>Heat sink layer</td>
<td>Al</td>
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</tbody>
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Proposed using magneto-static coupling in the heated region for the reversed aperture and exchange coupling for the front aperture [9]. This method has the merit that the carrier level for a long mark is not degraded because there is no masked area.

In RAD, the aperture is formed in the heated region while the cooler region is masked as shown in Fig. 4b. The information in the masked region is erased by the initializing magnet prior to the readout. The same C/N ratio as FAD was obtained which shows high resolving power in the tangential direction. Also, RAD has a major advantage in suppressing crosstalk from adjacent tracks. However, actual applications cannot use a permanent magnet with a magnetic field of more than 3 kOe which is required in the original version of RAD. Thus a practical RAD was proposed in which the initializing field is much reduced as described later [10, 19].

Another improvement in the RAD family was achieved using a magnetic double layer film which was named center aperture detection (CAD) [11]. The readout layer with an in-plane magnetization acts as a mask because no signal is read out from there, Neither an initializing field nor a readout field is necessary in CAD. A crosstalk of -30 dB for a 0.8-μm track was reported. An improvement in the resolving power in the tangential direction was reported by using double masked CAD (T-MSR) [12]. In addition to the front mask which originated from the in-plane magnetizing layer, a rear mask is
Fig. 5. Spatial frequency dependence of the relative carrier level for two wavelengths. The relative carrier approaches zero for conventional detection at the cut-off spatial frequency of \(2NA/\lambda\). The carrier for MSR by FAD expands beyond the cut-off.

formed in the heated region. As a result, a C/N ratio of 46 dB for 0.4-\(\mu\)m marks as well as low crosstalk were obtained.

**HIGH LINEAR DENSITY RECORDING ON FAD DISK**

We have been investigating the possibility of high linear density recording on FAD media, because the FAD disk with magnetic triple layers was easier to fabricate for us than the RAD disk with magnetic quadrilayers. We first tried to write by light intensity modulation. We confirmed that the relative carrier level for the FAD disk extends beyond the optical cut-off spatial frequency \(2NA/\lambda\), both for \(\lambda=780\) nm and \(\lambda=690\) nm, as shown in Fig. 5[13]. We investigated random data recording by (1,7)RLL mark length recording with a linear density of 0.27 \(\mu\)m/bit and optical parameters \(\lambda=690\) nm and \(NA=0.55\). The minimum mark length of 0.36 \(\mu\)m which corresponds to the bit length was near the optical limit of \(\lambda/(4NA)=0.31\) \(\mu\)m. The experiment was evaluated for an FAD disk with a track pitch of 1.15 \(\mu\)m by observing the jitter and the error rate as a function of the recording power as shown in Fig. 6[14]. The results indicate that a bit length of 0.27 \(\mu\)m can be read out by MSR but that the writing power margin is limited to \(\pm11.3\%\) by the light intensity modulation even after the improved writing compensation. Thus, we concentrated on magnetic field modulation associated with light pulse irradiation for recording the same bit length. Also, we utilized a substrate with a 0.85-\(\mu\)m track pitch and a 70-nm groove depth which was optimal for minimum crosstalk from adjacent tracks[15]. The recording power margin of the jitter for random data is shown in Fig. 7[16]. The three experiments indicated are recording first on the main track, then overwriting the main track with random data on adjacent tracks, and then recording on adjacent tracks with data on the main track written with minimum power. The total recording power margin as determined by the common margin for all three experiments was \(\pm25\%\). It is important to note that readout by MSR can be combined with recording by magnetic field modulation to obtain a higher linear density with a sufficient power margin. Another

Fig. 6. Jitter and bit error rate for an FAD disk as a function of the writing power by light intensity modulation.

Fig. 7. Jitter for an FAD disk as a function of the writing power by magnetic field modulation. The lower limit of the power margin is determined by overwritability. While, the upper limit is determined by crosstalk from adjacent tracks.
experiment confirmed that the power margin is not limited by crosswrite but by crosstalk[17]. This result suggests that the track density can be increased even further by adopting an RAD type MSR disk. Land/groove recording on an FAD disk by magnetic field modulation to achieve a 0.8-μm track pitch is discussed further in this symposium[17].

ADVANCES IN RAD FAMILIES

<table>
<thead>
<tr>
<th>Table I Classification of RAD families.</th>
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<tbody>
<tr>
<td>Single mask</td>
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<tr>
<td>Exchange coupling</td>
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<tr>
<td>Magneto-static coupling</td>
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<tr>
<td>Perpendicular front mask [22, 23]</td>
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</table>

Fig. 8. The mask structure of RAD for two readout power ranges at high and low linear velocities.

The RAD families shown in Table I are classified according to, (1) whether the mask shape is single mask or double mask, and (2) whether the coupling force between the readout layer and the recording layer is the exchange force or the magneto-static force.

The single and double mask states are shown schematically in Fig. 8 at relatively high and low linear velocities. At high linear velocity, the C/N ratio for a short mark abruptly increases at a critical read power $P_r$ and then shows a second increase of a few dB at $P>P_2$ when the rear mask appears. The double mask RAD has better resolving power in the tangential direction compared to the single mask RAD. At a lower linear velocity, however, the rear mask appears inside the aperture for $P>P_2$ which results in a decrease in the carrier level. Thus single mask RAD including CAD has been designed for applications at a relatively low linear velocity. Not only single mask RAD but also double mask RAD has lower crosstalk from adjacent tracks. Figure 9 shows the experimental conditions for recording on the wide grooves of an original RAD disk with a track pitch of 1.0 μm. A C/N ratio of more than 47 dB for a 0.4-μm mark and a crosstalk of -33 dB was obtained[18].

Regarding the coupling force between the readout layer and the recording layer in Fig. 3, it should be small enough in the cooled region so that the magnetization in the readout layer can be initialized by a low magnetic field. In contrast it should be large in the heated region so that the information in the recording layer is copied onto the readout layer. The exchange coupling generally decreases with an increase in the temperature, which is opposite to the desirable temperature dependence. This is the reason why a magnetic field of more than 3 kOe was necessary at the lower temperature for initializing the original RAD disk. A sophisticated tactic was employed in an RAD disk named Super MO by inserting an intermediate layer of GdFe to obtain the Kerr hysteresis loop shown in Fig. 10[19]. The switching field $H_{s2}+H_{c2}$ indicates the magnetic field where the magnetization of the readout layer and that of the intermediate layer are reversed at the same time. It can be expressed as

$$H_{s2}+H_{c2} = \frac{2(M_s h h_{c1} + M_{sr} h h_{c1}) + \sigma_{wi}}{2(M_s h_{r1} - M_{sr} h_{r1})}$$

where $M_s$, $h$, and $H_c$ are the magnetization, layer thickness, and the coercive force, respectively. Subscript $r$ and $i$ signify the readout layer and the intermediate layer, respectively. $\sigma_{wi}$ is the interface wall energy between the intermediate layer and the recording(writing) layer. $H_{s2}+H_{c2}$ diverges at a temperature where $M_s h_{r1} = M_{sr} h_{r1}$. It may actually be observed as shown in Fig. 11[19] when a rare-earth rich composition is used for the intermediate layer. As a result, the readout layer and the intermediate layer are initialized by a magnetic field less than 500 Oe for the front mask at low temperatures. The other switching field $H_{s1}+H_{c1}$ shown in Fig. 11 is expressed as

$$H_{s1}+H_{c1} = \frac{\sigma_{wr}}{2M_s h_{r}^{1/2} + H_{cr}}$$

where $\sigma_{wr}$ is the interface wall energy between the readout layer and the intermediate layer. The information in the read-
out layer is erased by the same magnetic field as the initializing field to form the rear mask at temperatures higher than 170°C as shown in Fig. 11. A C/N ratio of 47 dB for a 0.33-μm mark and a crosstalk of -30 dB for a 0.7-μm track pitch was achieved by light intensity modulation. This result suggests a bit length of 0.25 μm when (1,7)RLL mark length recording is adopted.

Since the magneto-static coupling between the readout layer and the recording layer is proportional to the magnetization of the readout layer, it is rather easy to control the temperature dependence of the magneto-static force by adjusting the compensation temperature of the readout layer. The magnetization of the readout layer is initialized by a small magnetic field of 100 Oe to make the front mask. The information in the recording layer is copied onto the readout layer at high temperatures to form the aperture. Signals for 0.4-μm marks with a track pitch of 1.1 μm were read with a leading edge jitter of 2 ns. In the case of an in-plane readout layer, the signal can be read out without a magnetic field[20].

A disadvantage of magneto-static coupling is that the coupling is not very large. A calculated example is shown in Fig. 13[12]. The coupling strength becomes insufficient when a written mark is long and wide. This dependence of the superresolution characteristics upon mark length is strong which may be a potential problem for the mark length recording. Fortunately, however, the mark size has been decreasing because of higher linear density and narrower track pitch. So the mark length dependence of the coupling might not be a hindrance.

PROSPECTS FOR HIGHER AREAL DENSITY

As shown in Fig. 1, optical disks with an areal density of 2 Gb/in² are being discussed for standardization. The technologies of the MO disk for this density have been almost finalized by optimizing the groove structure around a track pitch of 0.85-μm for minimum crosstalk typically using optics of λ=690 nm and NA=0.55. Areal densities of 3 to 4 Gb/in² are being proposed for the next generation of optical disks. MSR and land/groove recording are being heavily investigated to achieve such high densities.

As discussed in this paper, an FAD disk by magnetic field modulation recording could possibly attain 3 Gb/in². It was made clear that the track pitch is limited to 0.8 μm or more
length light source or a higher numerical aperture lens should be introduced to improve the modulation transfer function characteristics. Using optics which is currently available, land/groove recording combined with RAD may achieve a density more than 4 Gb/in². Since tolerance margins for disk tilt and off-track are rather narrow in land/groove recording, however, land/groove recording under actual drive system must be considered.

Although the writing power margin by magnetic field modulation is wider than that by light intensity modulation, the precise value required for the power margin depends on the design of the optical disk system. Since disk systems have become more intelligent these days, a power margin of ±10% by light intensity modulation may be permissible in a very high density system.

In conclusion, MSR, especially RAD, is expected to achieve an areal density of more than 4 Gb/in² for the huge capacity magneto-optical disk in the near future.

REFERENCES