Quadri-Value MO Recording Layers for Double-MAMMOS Readout Method

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Double-MAMMOS is an excellent method to increase memory density for MO recording. This method modifies the usual MAMMOS technique by applying double recording layers. Written domains in each recording layer can be selectively copied and expanded in a reading layer. By this method, memory density can be doubled. However, it is necessary to record twice, recording separately into two layers. Therefore, we propose a new type Double-MAMMOS disk, applying a quadri-value recording system to write the double recording layers with a single writing process. By applying a newly designed Double-MAMMOS disk, we can obtain a high density and high performance MO disk. To satisfy both functions of Double-MAMMOS and single writing process, we adapt the dependence of magnetization on temperature of films.

Key words: magneto-optical recording, thin film, multi-layer, domain expansion, MAMMOS, three dimensional recording

1. Introduction

Both increasing areal memory density and using three dimensional volumetric recording are important basic issues to achieve a memory of high density. The magnetic super resolution (MSR)\(^1\), the magnetic amplifying magneto-optical system (MAMMOS)\(^2\), and the domain wall displacement detection (DWDD)\(^3\) are superior methods to increase areal memory density. While the multi-value\(^4\) and the multi-wavelength readout\(^5\) are also eminent volumetric recording methods, there is no research to combine those methods. So we proposed Double-MAMMOS\(^6\), which combines the MAMMOS method with multi-layer recording. By using Double-MAMMOS, we have demonstrated a high density 100 Gb/in\(^2\) (50 Gb/in\(^2\) x 2 recording layers) MO recording\(^6\).

The proposed Double-MAMMOS consists of double recording layers different in T\(_{\text{comp}}\) and with one reading layer, as shown in Fig. 1. When a disk is irradiated by low reading power, as corresponds to T\(_1\) in temperature in Fig. 1 (a), the 2nd layer will not yield any stray field, because a compensation temperature of the 2nd layer T\(_{\text{comp}2}\) is set to T\(_1\). However, the magnetization of the 1st recording layer is not equal to zero at T\(_1\), so the information in the 1st recording layer will be copied and expanded in the reading layer by the yielded stray field. For the high reading power at T\(_3\), the 1st recording layer will not yield any stray field, so the information will be copied from the

![Fig. 1 Schematic representation of Double-MAMMOS, which can separately read out the information from two recording layers by changing read power.](image)

![Fig. 2 Schematic diagram of quadri-value recording disk.\(^4\) The 1st recording layer is usual MO film. The 2nd recording layer is exchange coupled with the assisting layer. Light for reading comes from the side of the 1st recording layer. The signal from the 2nd recording layer is detected from reflected light through the 1st recording layer.](image)
2nd recording layer to the reading layer. However, the two recording layers are written by a two-step process at the beginning of this study for the Double-MAMMOS. The 2nd recording layer, which has a high Curie temperature, is written by high recording laser power. In the next step, the 1st recording layer, which has a low Curie temperature, is written by low laser power. To increase writing speed, we propose a new Double-MAMMOS which applies the quadri-value recording layers for writing the double layer by single process.

2. Quadri-value recording

To write double recording layers by a single process, Shimazaki et al. proposed the quadri-value recording MO disk. Data are individually written in each recording layer without changing the focal point. All the recording layers settle within the depth of focus. The recording layer is selected by choosing both amplitude and direction of the external bias field, as shown in Fig. 2. For a large amplitude of the external field in A and D, the directions of the magnetization of written domains for both the 1st and 2nd layer are the same as the direction of the external field, as shown in Fig. 2 (1,1) and (0,0), respectively. However, for the case of a small amplitude of the external field in B and D, the directions of the magnetization of written domains for only the 2nd layer are in the opposite direction of the external field, as shown in Fig. 2 (1,0) and (0,1), respectively. This phenomenon is caused by a magnetic exchange coupling between the 2nd recording layer and assisting layer. Therefore, data are individually written in each memory layer by choosing both amplitude and direction of the external field without changing the focal point. In this way, the two recording layers of this new Double-MAMMOS disk can be written with single process by applying the quadri-value recording layers instead of the previous recording layers. However, this quadri-value recording method cannot be applied easily to Double-MAMMOS, because the assisting layer will yield some stray field which can make a copying error to the reading layer in the conventional system. We investigate how to combine the functions of the Double-MAMMOS and a single writing process without any yield for a stray field to a reading layer.

3. Applying quadri-value recording to Double-MAMMOS

We consider the layer structure of stacking a reading layer on the quadri-value recording layer, as shown in Fig. 3. In this method, a minimum written domain size in the exchange coupled 2nd recording layer depends on the thickness and magnetization of the 2nd recording layer. By choosing the right characteristics, a minimum domain size can be almost the same size of a conventional MO film.

Fig. 4 Schematic representation of a new proposed quadri-value MO recording system for the Double-MAMMOS.
To eliminate the stray field from the 1st recording layer for reading the 2nd layer, we select a rare earth rich (RE-rich) film, which has a compensation temperature as shown in Fig. 1. According to the principle of quadri-value recording 4), we need to chose combinations (1) or (2) at a recording temperature as follows: (1) a transition metal rich (TM-rich) 2nd layer, and an RE-rich assisting layer or (2) an RE-rich 2nd layer, and a TM-rich assisting layer at recording temperature. To not yield a stray field from the assisting layer, we adopt a compensation temperature of the assisting layer close to a reading temperature, so the assisting layer will be an RE-rich film at room temperature, and a TM-rich film at recording temperature, which corresponds to combination (2). In this case, the 2nd layer must be an RE-rich film at a recording temperature for quadri-value recording. This means that the value of magnetization of the 2nd recording layer can not become zero at $T \leq T_c$, because the film has no compensation temperature $T_{comp}$. Therefore, we should read the 1st layer at $T_1$ which leads a small value of magnetization of the 2nd layer, as shown in Fig. 4. We experimentally find a value of magnetization which can not copy any domains in a reading layer, and its value is less than 40 emu/cc. We adjust the characteristics of the magnetization depending on temperature to adapt the new Double-MAMMOS.

For reading the 1st layer, the temperature of the film rises up to $T_2$, where the magnetization of the 1st layer shows local maximum. At $T_2$, we chose a value of the magnetization of the 2nd and assisting layers at less than 40 emu/cc.

We set a readout temperature $T_1$ for the 2nd layer, as shown in Fig. 4. The magnetization and stray field of the 2nd layer at lower temperature $T_1$ are larger than those at a higher temperature $T_2$. $T_{comp}$ of the 1st layer and assisting layer are adjusted to $T_1$ to eliminate any stray field.

Under these guiding principles, we experimentally determined the thicknesses and compositions for the 1st, 2nd, and assisting layer.

4. Experimental results and discussion

4.1 Design of films

The quadri-value recording requires equations (1) and (2) under writing process.

$$M_{s2}h_2 < M_{sA}h_A \quad (1)$$

$$H_{c2} > H_{cA} \quad (2)$$

Where $M_{s1}$, $M_{sA}$: saturation magnetization, $h_2$, $h_A$: thickness, $H_{c2}$, $H_{cA}$: coercivity for the 2nd and assisting layers, respectively.

Keeping these conditions, we determined the compositions for the 2nd and assisting layers for an adaptive compensation temperature, as shown in Fig. 5. A compensation temperature of the assisting layer is set to 65 degrees C, because we demonstrated Double-MAMMOS using $T_1 = 65$ degrees C 6). Compositions of the 2nd layer and the assisting layer are TM-rich and RE-rich, respectively.

<table>
<thead>
<tr>
<th>2nd layer</th>
<th>Assist layer</th>
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<tbody>
<tr>
<td>SiN (20nm)</td>
<td>Tb$<em>{0.5}$Fe$</em>{0.5}$Co$_{0.5}$ (20nm)</td>
</tr>
<tr>
<td>Gd$<em>{0.7}$Fe$</em>{0.3}$Co$_{0.5}$ (50nm)</td>
<td></td>
</tr>
<tr>
<td>SiN (20nm)</td>
<td></td>
</tr>
<tr>
<td>glass substrate</td>
<td></td>
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Fig. 5 Exchange coupled MO film for the 2nd and assisting layers.

An exchange coupled recording film, which has a function of the quadri-value recording, indicates a special hysteresis loop in quadri-state, as shown in Fig. 6. This quadri-state corresponds to cases A, B, C, and D in Fig. 2. We observed this special hysteresis loop for this

![Hysteresis Loop](image)

Fig. 6 Schematic diagram of a special hysteresis loop for quadri-value recording for an exchange coupling recording film.

![Kerr Hysteresis Loop](image)

Fig. 7 Kerr hysteresis loop for the film SiN (20 nm) / TbFeCo (20 nm) for the 2nd recording layer / GdFeCo (50 nm) for the assisting layer / SiN (20 nm) / glass substrate.
exchange coupled film, as shown in Fig. 7. When the quadri-state loop can be observed, a direction of the magnetization of 2nd layer is in the same direction as the applied magnetic field in large applied fields for cases A and D. On the other hand, in applying small fields, the direction of the magnetization becomes opposite to the applied field for cases B and C. The dependence of the magnetization on temperature for Double-MAMMOS film, adapted by the new method, is shown in Fig. 8. At low temperatures, the magnetization $M_s$ for the 2nd layer shows large values, but $M_s$ of the other films is less than 40 emu/cc. Oppositely, at high temperatures, the $M_s$ of the 1st layer becomes large, and the $M_s$ of the other films is less than 40 emu/cc. This film has properties of Double-MAMMOS and multi-value recording, which can of write both the 1st and 2nd recording layer with single process.

Next, a readout simulation is performed to find the margin of Double-MAMMOS readout for this new proposed film.

4.2 Readout simulation

Readout process is simulated by a calculation of temperature distribution of absorption energy from an irradiating laser beam, stray field from magnetic layers, and distribution of coercive field $H_c$ of the reading layer using dependence of $H_c$ on temperature, as shown in Fig. 9.

Temperature distribution is calculated in a three dimensional heat flow under irradiation of Gaussian laser spot for 450 nm in diameter ($1/e^2$) in the film, as shown in Fig. 10. An A1Ti film is for a heat sink. This stacked layer structure is based on the previous Double-MAMMOS disk$^6$.

This simulation is performed in several steps as follows:
1) Calculation of absorption distribution for an irradiating laser power, including interference of multi-layer.
2) Calculation of three dimensional heat flow.
3) Calculation of magnetization distribution of the 1st, 2nd and assisting layer with or without domains.
4) Calculation of a stray field from the 1st, 2nd and assisting layer.
5) Calculation of a distribution of coercive field $H_c$ of the reading layer.
6) Comparison $H_c$ of the reading layer and a stray field from the 1st, 2nd and assisting layer.
7) Judgment of correct response or error response.

We simulated under the consideration of crescent shaped written domains of which the mark length is 50 nm and the mark width is 400 nm.

For example, one of the distributions for the total stray field from all the magnetic layers and $H_c$ for readout film are shown in Fig. 11. When the total field $H_t = H_s$ (stray field) + $H_b$ (bias field) is less than $H_c$ of the reading layer, as shown in Fig. 11 (a), a copying process can not be performed. We will say this error is a missing error.

![Fig. 8](image1.png) The dependence of the magnetization for the newly proposed quadri-value recording layers.

![Fig. 9](image2.png) Dependence of coercivity field $H_c$ on temperature for the GdFeCo readout layer.

![Fig. 10](image3.png) Stacking layer structure for simulation.
When $H_t > H_c$, as shown in Fig. 11 (b), a domain can be copied in the reading layer. This condition is the correct response. In case that there is no domain in recording layers, the condition of $H_t > H_G$ can happen by applying a bias field $H_b$ as shown in Fig. 11 (c). This case corresponds to an extra error. We simulated to know the condition which makes a correct response or an error under all combinations for existence of a written or not written domain in the 1st, 2nd, and assisting layers.

Readout margins depending on readout power and bias field $H_b$ are shown in Fig. 12. In this result, it is known that the 1st recording layer can be read under a readout power ranging from 1 to 1.6 mW. For the 2nd recording layer, a written domain can be copied to the reading layer under a readout power ranging from 0.4 to 0.75 mW. The new designed Double-MAMMOS can be read separately for the 1st and 2nd recording layer. These recording layers also have the functions of quadri-value recording, because the 2nd recording layer which is coupled with the assisting layer shows the quadri-state loop.

The bias margin for the 2nd layer is small. For reading the 2nd recording layer, the lower and upper limit of a bias margin is caused by missing errors and extra errors, respectively. This margin is mainly limited by missing errors, because values of magnetization $M_s$ of the 1st and assisting layer are small enough, and a value of $M_s$ for the 2nd layer is insufficient to make enough stray field to copy domains in the reading layer. Because of thermal diffusion, the temperature of the 1st recording layer is not as much as that of the 2nd recording layer. The temperature of the latter layer rises to the Curie temperature at 1.9mW in readout power. So a high readout power can destroy marks in the 2nd recording layer. For reading the 1st recording layer, a large bias...
margin is observed. The lower and upper limit of the bias margin for the 1st recording layer is extra errors and missing errors. This difference of error type between reading the 1st and 2nd recording layer is caused by the difference in polarity for a stray field of the layers.

To simulate an increasing stray field and to protect from damage of written domains in the 2nd recording layer, we change the characteristics of the 2nd layer, which has a Curie temperature of $T_c \sim 250$ degrees C, rather than $T_c$ of the previous film. By this change, we expect to increase a bias margin limited by missing errors. Increasing the $M_s$ of the 2nd recording layer can make an extra error for reading the 1st recording layer. To find the effect of this change for the 2nd layer, we calculated for the new condition, as shown in Fig. 13. By increasing $M_s$ of the 2nd layer, the bias margin becomes wider as expected. The lower limit of a bias field is changed from -50 to -100 Oe. This effect is caused by an increase in the stray field. As the bias margin for the 1st layer becomes small, an extra error appears by the stray field from the 2nd layer. However, the margin of the 1st layer is still enough.

By using this newly designed Double-MAMMOS disk, we expect not only to increase memory density, but also to increase recording speed with a single writing process.

5. Conclusion

We proposed the Double-MAMMOS disk which can be written for two recording layers with a single process by applying the multi-value recording disk method. An assisting layer in a multi-value recording disk yields some stray fields, and makes copying errors. We adapted the characteristics of the films by experiment and by simulation. We clarified the condition to achieve a new MAMMOS disk, Double-MAMMOS, which can be written for the two recording layers with a single process. A margin for readout is also shown by simulation.

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References


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