Read/Write Mechanism for a Scattered Type Super-Resolution Near-Field Structure Using an AgO\textsubscript{x} Mask Layer and the Smallest Mark Reproduced

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A working mechanism for a scattered type super-resolution near-field structure (super-RENS) disk using a silver oxide (AgO\textsubscript{x}) mask layer has been studied experimentally. The AgO\textsubscript{x} mask layer has five possible states depending on the laser power: AgO\textsubscript{x} (as-depo), uniformly dispersed Ag particles (after the initialization of 3.5 mW), Ag cluster (4–5 mW), Ag diffusion (5.5–7.5 mW), and a Ag ring structure (greater than 8 mW) for an objective lens numerical aperture of 0.5, a laser wavelength of 826 nm and a medium velocity of 2 m/s. On the other hand, the GeSbTe recording layer has the following possible states: crystal, half-way amorphous, completely amorphous, and gas bubble associated with Ag particles. For super-resolution read power (4 mW), the mask layer will have a Ag ring structure that increases both the signal carrier to noise ratio and the resolution limit. We improve the resolution limit of 413 nm to 50 nm at the duty ratio of 10% for the write optical pulse. [DOI: 10.1143/JJAP.44.197]

KEYWORDS: super-RENS, near field, super-resolution, Ag cluster, Ag ring, bubble pit, duty ratio, AgO\textsubscript{x}, GeSbTe, optical data storage

1. Introduction

The super-resolution near-field structure (super-RENS) is thought to have the capacity for super-high-density optical recording beyond the diffraction limit. For the aperture type super-RENS using an antimony (Sb) mask layer, the achievement of 90 nm mark length readout\textsuperscript{11} and the direct observation\textsuperscript{3} of the near-field aperture and the thermal lens\textsuperscript{2} formed on a Sb layer have been reported. The write phase change mechanism of the mask and recording layers and a read mechanism beyond the diffraction limit resolution have also been reported.\textsuperscript{5}

A scattered type super-RENS using a silver oxide (AgO\textsubscript{x}) mask layer\textsuperscript{5–7} has been proposed to significantly improve the carrier to noise ratio (CNR). The small metal particles in the gas bubble pit formed in the write process enhanced the near field (surface plasmons on the particles) as shown in the upper figure (a) of Fig. 1. Ho et al. found that the functional structure\textsuperscript{6} of AgO\textsubscript{x} depends on the write power as shown in the lower figure (b). The aggregated Ag nanocluster (having high reflectivity due to Ag dots) efficiently scatters the near field and the Ag ring (having high transmission due to a nanoaperture) not only confines the input laser beam so that it is thin, but also enhances the scattering field. Kataja et al. numerically studied the AgO\textsubscript{x} super-RENS phenomena using a 2D finite difference time domain (FDTD) method.\textsuperscript{3} They indicated that an AgO\textsubscript{x} super-RENS structure can be produced beyond the diffraction limit resolution when the aperture is surrounded by small Ag particles that are formed and filled with low-index materials such as O\textsubscript{2}.

The deformed gas bubble associated with metallic nanoparticles was also elucidated for a platinum oxide super-RENS disk. A CNR of over 47 dB for a mark length of 100 nm was obtained in an optical disk with the following structure: PC-substrate (0.6 mm)/ZnSiO\textsubscript{2} (130 nm)/AgInSbTe (40 nm)/ZnS–SiO\textsubscript{2} (20 nm).\textsuperscript{9,10}

Recently, Tominaga et al. have demonstrated a huge change in the refractive index generated in a focused laser spot and have proposed a ring aperture formed by a ferroelectric catastrophe\textsuperscript{11} in an AgInSbTe recording medium. This new super-resolution aperture can be observed between 350°C and 400°C, resulting in a second phase transition from a hexagonal to a rhombohedral structure. This type of optical disk has the following structure: PC-substrate (0.6 mm)/ZnSiO\textsubscript{2} (170 nm)/AgO\textsubscript{x} (15 nm)/ZnS–SiO\textsubscript{2} (20 nm), along with results obtained from systematic experiments under various read/write conditions. We also present the smallest mark formation of 50 nm length due to the use of optical pulses with a reduced duty ratio.

2. Initialization Effect

To explain the super-RENS mechanism directly and clearly, the read/write characteristics have been scrutinized experimentally. The configuration for a super-RENS optical
disk using an AgOx mask layer is shown in Fig. 2. The optical disk parameters are shown in Table I. The objective lens numerical aperture is $NA = 0.5$, the laser wavelength is $\lambda = 826 \text{ nm}$, and the medium velocity is $v = 2 \text{ m/s}$. Therefore, the optical diffraction limit $\lambda/4NA$ of our experiments is 413 nm.

Figure 3 shows the reproduced signals (normalized with as-depo reflectivity) at different initializations of laser power $P_i$ for an as-depo medium. The reproduced signal $V_1$ (mark) at the read power $Pr = 1 \text{ mW}$ changes in ways such as the following: (a) becomes small negative at $P_i = 2.5 \text{ mW}$, (b) becomes maximum positive at $P_i = 3.5 \text{ mW}$, (c) becomes nearly zero at $P_i = 4 \text{ mW}$, and (d) gradually increases to negative as $P_i$ increases. This variation generated by the written mark is shown in greater detail by the curve “mark” in Fig. 4. This figure shows the effect of initialization on an as-depo medium of the super-RENS disk. The mark reflectivity $V_1$, normalized with as-depo reflectivity $V_1$, changes from (a) a small negative to zero to (b) positive to (c) zero to (d) increases to negative and then becomes saturated as the laser power increases.

This phenomenon corresponds to (a) the little decrease in reflectivity due to the little amorphous process in GeSbTe and then its cancellation due to the increase in reflectivity with the AgOx decomposition (Ag particles), (b) fully decomposed Ag particles, (c) cancellation due to the half amorphous process in GeSbTe, (d) the decrease in reflectivity due to the completely amorphous process in GeSbTe. The maximum positive of the laser power of 3.5 mW shows that the AgOx is fully decomposed to Ag particles and O2, both of which are uniformly dispersed in the mask layer. On the other hand, the non-mark reflectivity $V_2$ remains constant because thermal interference due to the successive laser pulses does not occur for long (3000 nm) marks at the duty ratio of 50%.

Figure 5 shows the relationship between the CNR for the super-RENS readout ($Pr = 4 \text{ mW}$) and the initialization laser power $P_i$. We define $P_i = 3.5 \text{ mW}$ as the initialization laser power where the CNR for the short mark (under the diffraction limit) reaches its maximum. The maximum CNR corresponds to a reproduced signal maximum at $P_i = 3.5 \text{ mW}$ in Fig. 4, where fully decomposed Ag particles are dispersed in the mask layer.

Figure 6 shows the effect of initialization on the CNR for the super-RENS readout, with the write power $P_w$ as a parameter. The CNR with initialization (b) is higher and less dependent on $P_w$ than that without initialization (a). Moreover, we can detect a mark length of 200 nm (duty ratio 50%) because with initialization the resolution increases.

<table>
<thead>
<tr>
<th>Laser Beam (λ=826 nm)</th>
<th>Reflectivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 mW</td>
<td>100</td>
</tr>
<tr>
<td>2.0 mW</td>
<td>90</td>
</tr>
<tr>
<td>3.0 mW</td>
<td>80</td>
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<td>4.0 mW</td>
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<td>50</td>
</tr>
<tr>
<td>7.0 mW</td>
<td>40</td>
</tr>
<tr>
<td>8.0 mW</td>
<td>30</td>
</tr>
<tr>
<td>9.0 mW</td>
<td>20</td>
</tr>
</tbody>
</table>

Fig. 4. Initialization effect on as-depo medium of super-RENS optical disk.

Fig. 5. Relationship between super-RENS CNR ($Pr = 4 \text{ mW}$) and initialization laser power $P_i$.
3. Write Power Dependence

To determine the amorphous level of the recording layer, we measured the write power dependence of signal amplitude $V_{pp}/V_i$ and the CNR for the initialized medium. Here, $V_{pp} = V_1 - V_2$, and $V_1$ is the as-depo level. They were measured under two conditions: immediately after writing (observed at $Pr = 1$ mW) and at super-RENS readout (observed at $Pr = 4$ mW). We compared the two signals and estimated the phase level (signal) and the noise level of the medium.

Figure 7 shows the relationship between (a) \(CNR\), (b) $V_{pp}/V_i$, and write power $P_w$ at the read power of $Pr = 1$ mW. Figure 8 shows the relationship between (a) \(CNR\), (b) $V_{pp}/V_i$, and write power $P_w$ at $Pr = 4$ mW, where mark length is a parameter. Upper figure (a) shows that a dip appears for every mark length. This phenomenon occurs because reflectivity decreases as the half amorphous process for middle $P_w$, but it increases as the Ag cluster process for high $P_w$. Then the \(CNR\) becomes constant for high $P_w$. This suggests that the noise level increases for high $P_w$ because the reflectivity (signal level) was found to increase with the completely amorphous process as $P_w$ increases, as shown in the lower figure (b). We also find that the signal remains constant between 5.5 mW and 7.5 mW for a long mark at $Pr = 1$ mW. This suggests that some changes occurred, which are described later, in the mask layer between 5.5 mW and 7.5 mW write process.

In the case of the super RENS readout ($Pr = 4$ mW), we find that every dip disappears as shown in the upper figure (a) of Fig. 8. Moreover, we find that the signal increases as $P_w$ increases due to the completely amorphous process, as shown in the lower figure (b). We confirm that the constant signal level between $P_w = 5.5$ mW and 7.5 mW, which appeared in the lower figure (b) of Fig. 7, is a result of the reflectivity decreasing as the Ag cluster is decomposed and diffused due to the great heat generated at the continuous read power of $Pr = 4$ mW. We define the optimum write power as $P_w = 8.5$ mW, at which the \(CNR\) for the shortest mark of 200 nm reaches maximum as shown in the upper figure (a) of Fig. 8.

4. Read Power Dependence and Super-RENS Mechanism

Figure 9 shows the read power $Pr$ dependence on the \(CNR\) of the mark written at the power of $P_w = 8.5$ mW, where mark length is a parameter. From the figure, it is evident that beyond the diffraction limit, signals (400–200 nm) appear and the highest \(CNR\) of each mark length can be obtained at $Pr = 4$ mW. On the other hand, \(CNR\)s are high and almost independent from $Pr$ for long marks (1000–3000 nm). All the signals disappear at read powers greater than $Pr = 6.5$ mW because the amorphous mark and the bubble pit are erased due to the continuous large $Pr$. On the basis of these results, we define the optimum super-RENS read power as 4 mW.
Figure 10 shows the read power dependence on the signal spectrum and the amplitude for the mark lengths of (a) 1000 nm and (b) 200 nm, where read power $Pr$ as a parameter. Both the signal spectrum and the signal amplitude increase at $Pr = 4$ mW. On the other hand, we find that noise increases at $Pr = 6$ mW in the spectrum in the upper right figure and the signal amplitude decreases due to the degradation of the resolution (Ag cluster size increases).

On the basis of these results, we propose a model for a super-RENS mechanism using a AgO$_x$ mask layer. Figure 11 shows the states just after writing ($Pr = 1$ mW) for both the mask layer and the recording layer, with write
power $P_w$ as a parameter. The working mechanism for the super-RENS using the AgO$_2$ mask layer is as follows. Both the mask and the recording layer have five possible states depending on the write power $P_w$: (a) as-depo, (b) Ag particles uniformly dispersed and crystallized (after initialization $P_i = 3.5$ mW), (c) Ag cluster and half amorphous ($P_w = 4$–5 mW), (d) Ag diffusion and completely amorphous ($P_w = 5.5$–7.5 mW), and (e) Ag ring and bubble pit (greater than $P_w = 8$ mW). The mask layer for the super-RENS readout ($P_r = 4$ mW) has an Ag ring structure, and the aperture is filled with O$_2$, which increases both the CNR and the resolution limit.

5. Optical Pulse Duty Dependence

To realize a short mark length, we illuminated thermally isolated optical pulses (having a decreased duty ratio). Figure 12 shows the relationship between reflectivity $V_1$ (non-mark), $V_2$ (mark), and mark length for super-RENS readout ($P_r = 4$ mW), with optical pulse duty as a parameter.

![Fig. 12. Relationship between reflectivity $V_1$ (non mark), $V_2$ (mark), and mark length for super-RENS readout ($P_r = 4$ mW), with optical pulse duty as a parameter.](image)

Fig. 12. Relationship between reflectivity $V_1$ (non mark), $V_2$ (mark), and mark length for super-RENS readout ($P_r = 4$ mW), with optical pulse duty as a parameter.

(1) The mask layer and the recording layer have five possible states depending on the write power $P_w$: as-depo, Ag particles uniformly dispersed and crystallized (after initialization), Ag cluster and half amorphous, Ag diffusion and completely amorphous, and Ag ring and bubble pit.

(2) The mask layer for the super-RENS readout has a Ag ring structure, and the aperture is filled with O$_2$, which increases both the CNR and the resolution limit.

(3) The smallest mark length of 50 nm is reproduced with 17 dB by decreasing the optical pulse duty ratio of 10% under the experimental condition of $\lambda/4NA = 413$ nm.

6. Conclusions

A working mechanism for a scattered type super-resolution near-field structure (super-RENS) using ZnSiO$_2$/AgO$_2$/ZnSiO$_2$/GeSbTe/ZnSiO$_2$ is clarified, and the smallest mark of 50 nm is reproduced for the initialization power of $P_i = 3.5$ mW. The results obtained are summarized as follows:

![Fig. 13. Relationship between CNR and mark length for super-RENS readout ($P_r = 4$ mW), with optical pulse duty as a parameter.](image)

Fig. 13. Relationship between CNR and mark length for super-RENS readout ($P_r = 4$ mW), with optical pulse duty as a parameter.

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