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Restriction of shot noise and material noise in a multilevel photochromic memory on signal-to-noise ratio*

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The recording density of multilevel photochromic memory is limited by the signal-to-noise ratio (SNR) of the readout signal. In this paper, shot noise and material noise are investigated through theoretical analysis of SNR. When the bandwidth of a system is less than 1MHz, the material noise takes a prominent position; when the bandwidth of the system is more than 10MHz, the shot noise becomes dominant. The thickness of recording layer can be optimized to maximize the SNR and reduce the influence of the bandwidth of the system on SNR.

Keywords: photochromic memory, multilevel recording, bandwidth of system
PACC: 4230N

1. Introduction

Continuous efforts have been made to increase the recording density of optical memories in order to satisfy the ever-growing demands for high-speed and large-data computing, as well as for high-quality video recording. In conventional optical recording an increment in recording density is achieved by reducing the recording mark size.[1] Multilevel recording[2−9] is a new approach to increasing the storage capacity. It can improve the recording density without changing the recording mark size. Binary coding is widely used in conventional optical memory, which has only two possible states in a single recording region, and each recording region corresponds to one bit data. However, multilevel recording has $M(M > 2)$ possible states in each recording region, and each recording region corresponds to $\log_2 M$ bits data.

Multilevel recording can be implemented by using different amplitudes or phases of reflective light. It can be used in the photochromic memory.[9] Photochromic materials characteristically exhibit either of two chemical forms that are reversibly transformed from one to another on being irradiated by a light with an appropriate wavelength. Photochromic materials have been applied to high-density optical memories due to their potential in high resolution, high sensitivity and multiplexed recording.[10−14] The photochromic memory can utilize specific characteristics of light, such as wavelength, polarization and phase to add the capacity of storage, with the recorded mark size fixed. Multilevel recording used in photochromic memory can increase the recording density further.

The recording density of multilevel recording for photochromic memory is limited by the signal-to-noise ratio (SNR). Shot noise and material noise inevitably exist in the multilevel photochromic memory, whose restriction on SNR originates from a quantum mechanism due to the fluctuations in the number of generated electrons and the chromophore concentration. Tsujioka *et al* have theoretically investigated the restriction of these two noises on SNR in photochemical hole-burning memory and in near-field photochromic memory.[15−17] But they cannot be used in photochromic multilevel memory directly. In this paper we try to theoretically clarify the restriction of these two noises on the SNR in photochromic multilevel memory.

2. Principle of multilevel photochromic memory

Photochromic material has two stable states, A and B, as shown in Fig.1. Their absorbances to the light at a particular wavelength λ are quite different.

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State A can change into state B after the material absorbs the light at the particular wavelength, while state B can change into state A when the light at another wavelength is absorbed. Therefore, the difference in absorbance between the two states can be utilized to record data.

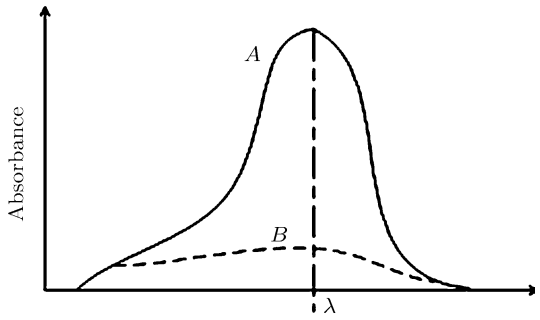


Fig.1. Principle of photochromic memory.

The conversion of the two states into each other is achieved by absorbing light with a wavelength λ. The molecules in state A are converted into the molecules in state B in photochromic recording. The absorbance to light of photochromic medium is determined by the ratio of the number of molecules in state A to those in state B. In the information recording process, the ratio in a recording region can be controlled by using a special writing scheme; then, a multilevel reflectivity in recording marks is achieved, which can be read out by an optical system as shown in Fig.2.

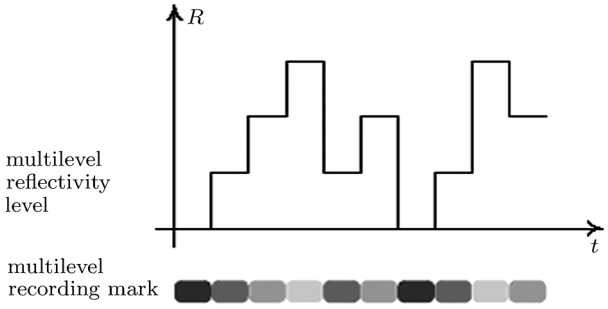


Fig.2. Reflectivity level of multilevel recording in photochromic medium.

The structure of a photochromic medium for multilevel recording is illustrated in Fig.3. In a recording region, the focused incident light transmits the recording layer twice due to the existence of reflective layer. Because the reflective layer has a reflectivity as high as 99% and the reflection of the upper surface of the recording layer can be omitted, the reflection of the medium is considered as the transmission of two recording layers as shown in Fig.4. In the model of an optical readout system for multilevel photochromic memory, the incident light with power P transmits the recording layer twice and is received by the photodiode in the optical system. The minimum diameter of the focused light spot on the recording layer, d, is determined by

$$d = 1.22\frac{\lambda}{NA} \tag{1}$$

where λ is the wavelength of incident light and NA is the numerical aperture.

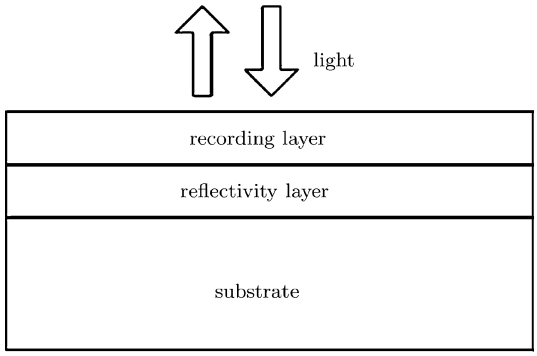


Fig.3. Structure of a photochromic medium for multilevel recording.

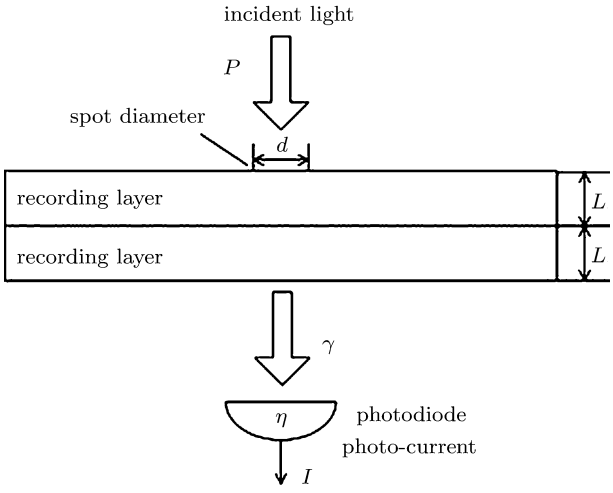


Fig.4. Model of an optical readout system for multilevel photochromic memory.

3. Theoretical estimate

It is assumed that almost all photochromic molecules in the recording layer stay in state A. In a recording process, the number of molecules in state B increases and the number of molecules in state A decreases because of absorption of photons. The minimal and maximal values of the concentration of molecules in state A are defined as $C_{\min}$ and $C_{\max}$ respectively. Supposing that the number of levels recorded in the recording layer is M, the concentration of molecules in state A corresponding to each multilevel recording area can be described by C_0, C_1, ...,

C_{M-1}, respectively, as follows:

$$C_i = C_{\min} + \frac{\mathrm{i}(C_{\max} - C_{\min})}{M-1}, \quad i = 0, 1, \ldots, M-1. \tag{2}$$

And the transmittance of the recording layer is given by

$$T_i = \exp(-2.303 \times \varepsilon L C_i), \quad i = 0, 1, \ldots, M-1, \tag{3}$$

where ε is the molar extinction coefficient of the photochromic materials, and L is the thickness of the recording layer.

The detected photocurrents I_i $(0 \le i \le M-1)$ corresponding to those multilevel recording areas are

$$I_i = e\eta \frac{P\lambda}{hc} \gamma T_i^2, \quad i = 0, 1, \ldots, M-1 \tag{4}$$

where e is the elementary charge (1.6×10^{-19}C), η photoelectric conversion efficiency of the photodiode, P laser power, h Planck constant (6.63×10^{-34}J), c speed of light in vacuum and γ pickup efficiency of the optical system.

The signal current is determined by the minimal value among differences between any two photocurrents expressed by Eq.(4):

$$I_{\text{signal}} = \min_{\substack{0 \le i,j \le M-1 \\ i \ne j}} \left| I_i - I_j \right| = e\eta \frac{P\lambda}{hc} \gamma \cdot \min_{\substack{0 \le i,j \le M-1 \\ i \ne j}} \left| T_i^2 - T_j^2 \right|. \tag{5}$$

Shot noise is caused by the quantum fluctuations of photons detected by the photodiode. Materials noise, which was first introduced by Murase[17] to estimate the restriction of recording density on photochemical hole-burning memory, originates from the statistical fluctuations of the photochromic molecule concentrations. In the multilevel photochromic memory the material noise depends on the fluctuation of recording power, recording time and the inhomogeneity of recording layer.

The shot noise currents corresponding to the M level marks in recording layer are

$$I_{\text{shotnoisei}} = e \left[2\eta \frac{P}{h\nu} \gamma T_i^2 B \right]^{1/2}, \quad i = 0, 1, \ldots, M-1, \tag{6}$$

where B is the bandwidth of the system. Because the signal current is only deteriorated by the adjacent noise current, the total shot noise current is determined by

$$I_{\text{shotnoise}} = \left[\max(I_{\text{shotnoisei}}^2 + I_{\text{shotnoisei+1}}^2) \right]^{1/2} = \left[2e^2\eta \frac{P}{h\nu} \gamma B \cdot \max(T_i^2 + T_{i+1}^2) \right]^{1/2}, \quad i = 0, 1, \ldots, M-2. \tag{7}$$

In the analysis of the material noise current, it is assumed that the smallest recorded mark volume is of a cylinder with a diameter d as expressed in Eq.(1). The number of the photochromic molecules in state A in this volume, N, is

$$N = N_{\mathrm{A}} C L \frac{\pi}{4} \left(0.61 \frac{\lambda}{NA} \right)^2, \tag{8}$$

where N_{A} is Avogadro constant ($6.02 \times 10^{23}\mathrm{mol}^{-1}$). The fluctuation of N is expressed as the Poisson distribution and given by[16]

$$\delta N = \sqrt{N}, \tag{9}$$

The fluctuation of the squared transmittance δT_i^2 in an unrecorded area can be obtained by Eqs.(4), (8) and (9) as

$$\delta T_i^2 = \left| [T_i^2(N+\delta N)]^2 - [T_i^2(N)]^2 \right| = \exp(-4.606\varepsilon L C_i) \left[1 - \exp\left(-3.279\varepsilon \sqrt{\frac{LC_i(NA)^2}{\pi N_{\mathrm{A}} \lambda^2}} \right) \right], \quad i = 0, 1, \ldots, M-1. \tag{10}$$

So the material noise current can be obtained from $\delta T_i (0 \leq i \leq M-1)$ as follows:

$$I_{\text{matnoisei}} = e\eta \frac{P\lambda}{hc}\gamma \delta T_i^2 = e\eta \frac{P\lambda}{hc}\gamma \exp(-4.606\varepsilon K C_i)\left[1 - \exp\left(-3.279\varepsilon\sqrt{\frac{LC_i(NA)^2}{\pi N_{\text{A}}\lambda^2}}\right)\right], \quad i = 0, 1, \ldots, M-1. \tag{11}$$

Because the signal current is deteriorated only by the adjacent noise current, the total material noise current is determined by

$$I_{\text{matnoise}} = e\eta \frac{P\lambda}{hc}\gamma \cdot \max\left\{\left[(\delta T_i^2)^2 + (\delta T_{i+1}^2)^2\right]^{1/2}\right\}, \quad i = 0, 1, \ldots, M-1. \tag{12}$$

From Eqs.(6) and (12), the noise current containing the shot noise and the material noise is obtained by

$$\begin{aligned} I_{\text{noise}} &= (I_{\text{shotnoise}}^2 + I_{\text{matnoise}}^2)^{1/2} \\ &= \max\left\{2e^2\eta \frac{P\lambda}{hc}\gamma(T_i^2 + T_{i+1}^2)B + \left(e\eta \frac{P\lambda}{hc}\gamma\right)^2\left[(\delta T_i^2)^2 + (\delta T_{i+1}^2)^2\right]\right\}^{1/2}, \ i = 0, 1, \ldots, M-2. \end{aligned} \tag{13}$$

The SNR is the ratio of the signal current expressed by Eq.(5) to the noise current expressed by Eq.(13), i.e.

$$\text{SNR} = \frac{\min\limits_{0\leq i,j\leq M-1 \ i\neq j}\left|T_i^2 - T_j^2\right|}{\max\limits_{0\leq k\leq M-2}\left\{\sqrt{\dfrac{2hcB}{\gamma\eta P\lambda}(T_k^2 + T_{k+1}^2) + \left[\left(\delta T_k^2\right)^2 + \left(\delta T_{k+1}^2\right)^2\right]}\right\}}. \tag{14}$$

The multilevel recording can increase the recording density with the increase of M. However, the larger the M is, the higher the SNR is required in multilevel memory. Simulations showed that the SNR had to be over 28.7dB in an 8-level memory and over 32.0dB in a 12-level memory,[18] otherwise, the recording density was less than the theoretical value ($\log_2 8 = 3$ or $\log_2 12 = 3.59$). It is the SNR that limits the recording density in the multilevel photochromic memory.

4. Numerical calculation and analysis

Figures 5 and 6 show SNR vs the bandwidth of system for different thickness of record layer. An increment in bandwidth of system B can raise the shot noise and decrease the SNR. When L is 3 μm, the SNR decreases sharply with the increase of B. When B exceeds 0.1MHz, the SNR is lower than 32 dB for M = 12, so that the quality of readout signals cannot meet the requirement in the 12-level memory. When B is over 0.84 MHz, the SNR is lower than 28.7 dB for M = 8, so that it can be used only in the 8-level memory with a low bandwidth. It means that the recording density in the photochromic multilevel memory is restricted by the shot noise and material noise.

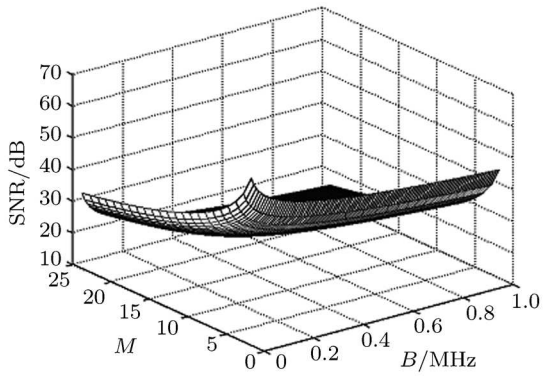


Fig.5. SNR vs the number of level and the bandwidth of system ($L = 3\mu$m).

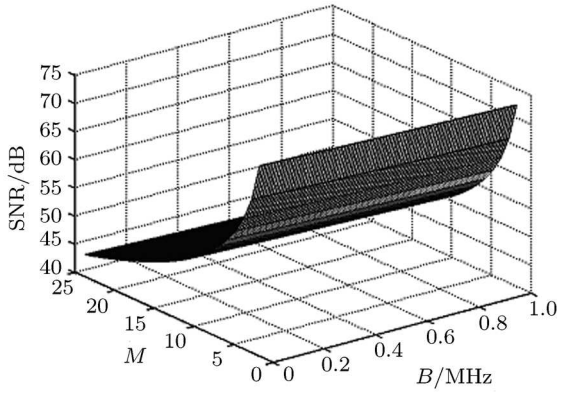


Fig.6. SNR vs the number of level and the bandwidth of system ($L = 0.5\mu$m)

However, when L is 0.5 μm, the SNR does not change approximately with B as long as M is constant as shown in Fig.6. The reason is that when B is less than 1MHz, a reduction in thickness of the recording layer can not only improve the SNR but also reduce effectively the shot noise restriction on SNR. So it is very important to choose an appropriate thickness of recording layer for the improvement of SNR.

Figure 7 shows SNR vs thickness of the record layer L and number of level M, for B = 0.01 MHz, 1 MHz, 10 MHz and 100 MHz, respectively. When B is less than 1 MHz, the material noise is prominent in comparison with the shot noise. The SNR varies mainly with L. The SNR is not a monotone function of L, and it reaches a maximum when L is about 400 nm. Although an appropriate L can reduce the restriction of B, the bandwidth of the system of over 10 MHz can cause the prominent falling of SNR.

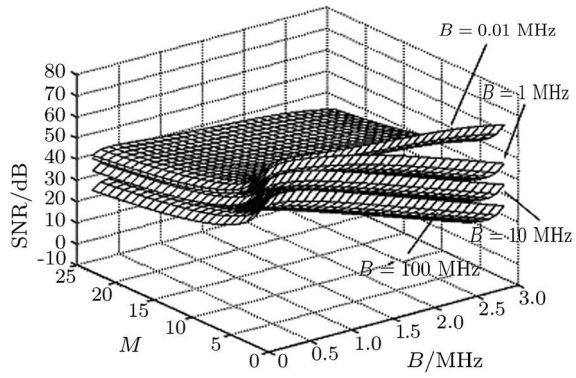


Fig.7. SNR vs the number of level and the thickness of recording layer.

Figure 7 shows that, when B is over 100 MHz, the SNR cannot meet the requirement in the multilevel memory. Therefore, even if the value of L is optimized, the shot noise restriction must be taken into account when B is over 10 MHz.

As stated above, the required value of SNR increases with the increase of M. But from Fig.5, Fig.6 and Fig.7, it is shown that the value of SNR actually decreases with the increase of M. It means that there exists a threshold value of M for each group of B and L. M that is more than the threshold cannot be achieved in multilevel photochromic memory due to the limit of SNR. The threshold value depends on the signal detection method and the performance of the signal processing system.

5. Conclusions

SNR of readout signals restricts the recording density in a multilevel photochromic memory. The shot noise and material noise can decrease the threshold value of M and reduce the recording density. Their restrictions on the SNR are related to the thickness of recording layer and bandwidth of system. When the thickness of recording layer is about 400 nm, the SNR reaches peak values. When B is less than 1MHz, an appropriate thickness of recording layer can reduce the restriction of the bandwidth of the system on the SNR. However, when B is over 100 MHz, the SNR cannot meet the requirement in the multilevel photochromic memory.

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