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Multilevel read-only optical recording methods*

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The advantages of read-only storage is the predominance of optical recording relative to magnetic and other rewritable methods. Multilevel (ML) read-only technology has been a trend to improve the data capacity and transfer rate. Based on the principle and coding method of ML, this paper demonstrates some ML read-only recording methods, of which a new ML read-only recording is developed. This recording method integrates amplitude modulation achieved by the reaction mechanism of physics and chemistry of photoresist with the run-length-limited technology. The discs can be achieved using standard photoresist mastering and replication techniques with great compatibility to conventional binary read-only discs.

Keywords: multilevel optical recording, read-only, amplitude modulation
PACC: 4230N, 4280T, 4260F

1. Introduction

Read-only discs are movable and can be manufactured using low-cost production methods such as stamping, which is convenient for issuance of information. These functions are the particular features of optical recording compared with other memory methods such as magnetic and flash recording. In optical recording, the user data capacity C can be expressed as

$$C = R \times \frac{A}{S} \times N \times \log_2 M, \tag{1}$$

where R, A and N are the storage efficiency, areas of recording and layers of recording respectively, which are all constants in a given recording method. S and M are the size of recording marks and the storage levels respectively. The conventional technology to increase the capacity is to minimize S; however, this is limited by the optical diffraction radius.[1,2] Another way is to enlarge the number of recording levels. The number of bits, which each recording mark corresponds to, is proportional to the logarithm of M according to formula (1). For a conventional disc, two states of mark and null are realized by the high and the low levels of reflected light, which means that each mark corresponds to one bit. Multilevel ($M > 2$) can increase the information contained in one mark, through which the spatial density and transfer rate can be increased greatly.

2. Principle and means for multilevel read-only optical storage

The key of multilevel (ML) storage is to increase the number of states one recording cell can represent. The more the states, the larger the capacity. In a read-only optical storage, some characteristics, such as the optical and electrical properties, of the readout signal can be adopted to store information. Figure 1 demonstrates the principle of binary and ML storage schemes. When the readout signal includes more than two types of state parameters, it can be used for ML recording.

As early as in 1995, McLaughlin studied the M-ary codes, which are the base of multilevel storage.[3] M-ary codes are similar to the conventional binary run-length limited (RLL) codes, but make use of M possible signal levels. For a specified minimum time $t_{\min}$, the density of such codes depends primarily on the number of levels M and the values of $t_{\min}$. At a given recording velocity, the time parameter $t_{\min}$ corresponds to 1T of the length of recording mark on discs.

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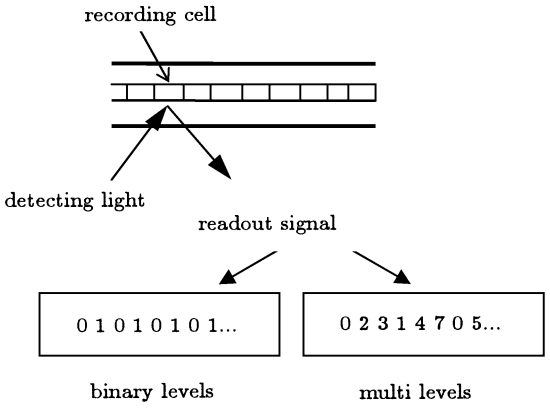


Fig.1. The principle of binary level and ML storage.

In ML discs, with different values of parameters in coding, the user data can be coded and stored by changing the physical parameters of the discs.

The relatively simple read-only ML method is called pit depth modulation (PDM).[4] The different levels in PDM correspond to different reflectivity responses of the readout signal, which are achieved by varying pit depth from zero to approximately 1/4-wavelength depth in the medium, as shown in Fig.2. The pits have identical lengths which are all made in $t_{\min}$ and are written end-to-end to form a continuous groove. The variant shades of grey indicate different levels on the surface profile of recording.

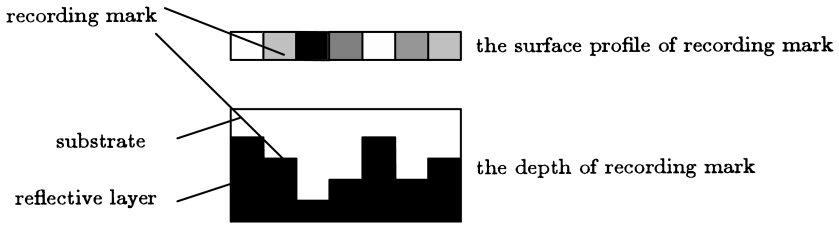
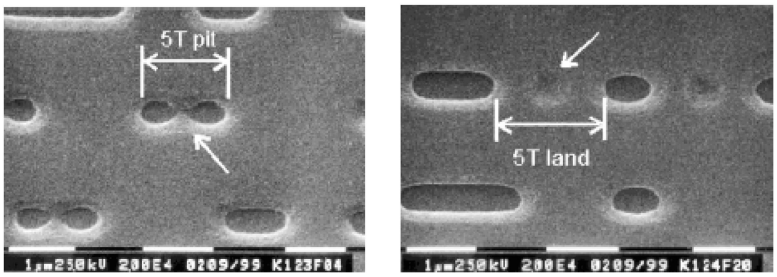


Fig.2. The principle of PDM.

In order to increase the number of levels in PDM, several methods for improving the resolution limit of pit depth have been proposed. One method is to utilize the phase difference of orthogonal polarizations of reflected light.[5] Since the phase difference ranges from $-\pi/2$ to $\pi/2$, the number of levels is expected to be high. Another method is called pit edge and depth modulation (PEDM), which combines readout signal and a tangential push-pull signal to make the minimum pit length shorter.[6] Thus, based on the depth modulation technology, a larger recording density and a higher transfer rate are achieved.

Besides the diverse depths of recording mark, the surface profile of recording can be varied too. The limited multi level (LML) is to introduce multilevel effects to the long pit and land runlengths of the main RLL channel, by which two additional LML channels are achieved, as shown in Fig.3.[7] In LML-coding, a two-level modulation is applied to pits and lands, accommodating a signal LML-bit for each long runlength (LML-bit=0 for non-modified amplitude. LML-bit=1 for a reduced absolute amplitude). The capacity is dependent on the occurrence of long runlengths in the RLL channel. However, only the marks longer than 5T can be utilized with an improvement in capacity about 20%. There are some other methods that achieve ML signal through variable surface profiles such as groove baseband recording (GBR) shown in Fig.4.[8]



(a) 5T pits in LML (b) 5T lands in LML

Fig.3. The principle of LML.

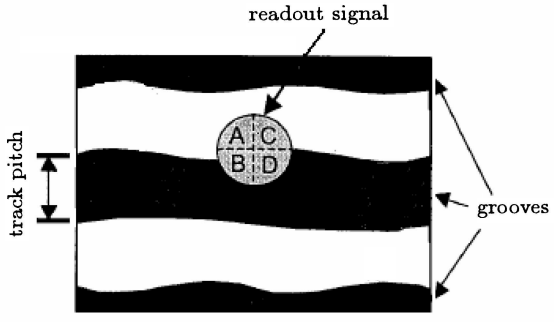


Fig.4. The principle of GBR.

3. A new ML RLL read-only storage method

3.1. The principle of ML RLL read-only storage

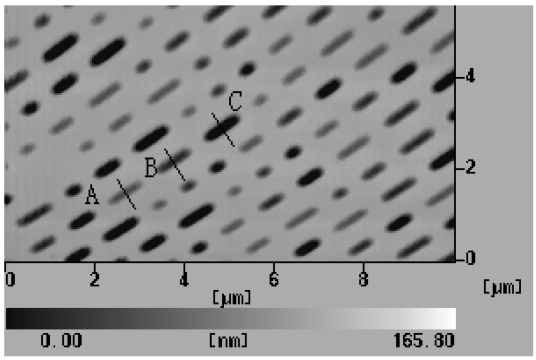
Integrating the technologies of varying the pit depth and surface profile stated above simultaneously, the dynamic range of reflectivity of readout signal in read-only disc is greatly enlarged and the different levels corresponding to different reflectivity responses can be obviously increased.

This storage method is adopted in conventional DVD. When positive photoresist is irradiated by laser beams with different power, micro-patterns such as the depth and the width of the irradiated region in the transverse surface are varied, which can be employed for ML read-only discs due to the different readout signals. The depth and radius of the penetration in the reactive photoresist are both increased when the laser power is increased, so it is easier to keep the two parameters changed at the same time in processing than to keep one. Moreover, the reflectivity of readout signal has a larger dynamic range in depth and width modulations.

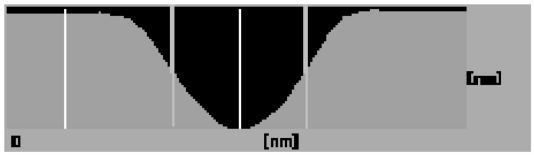
Combined with the RLL technology in traditional optical discs, which is achieved by changing the pulse width of laser beam, ML can increase recording capacity greatly.

3.2. Realization of ML-RLL read-only disc

On the conventional binary modulation the profile of recording pits is the same in depth and width, but different in length. In M-ary RLL modulation there are $M-1$ types of profiles of recording pits (except for lands) because M amplitudes of readout signal for each run-length are required. Figure 5 shows the transverse sizes of ML recording marks with the same length. ΔZ and distance in Fig.5(c) are the depth and the full width at half height shown in Figs.5(b) and 5(c) of marks A, B and C, are three different laser powers, 0.83, 1.0 and 1.17mW respectively for recording. Table 1 lists the parameters used in the experiment.



(a)



(b)

	ΔZ/nm	distance/nm
A	65.39458	201.7046
B	97.45010	251.5509
C	123.6519	285.2020

(c)

Fig.5. The transverse parameters of recording marks measured by AFM.

Table 1. Parameters used in experiment.

substrate	SiO_2	
photoresist	kind	microposit S1813
	thickness	130nm
exposure	wavelength of laser (λ)	405nm
	numerical aperture (NA)	0.9
development	developer	3:1 D.I. water: microposit developer concentrate
	temperature	22°C
	time	12seconds
recording speed	3.52m/s	

The micro-patterns are significantly different in depth and width. These profiles depend on the power modulation of writing laser, as illustrated in Fig.6(a). Four power levels of writing laser in mastering correspond to four profiles (including land) of recording marks. And the light intensities reflected from the recording mark with different profiles are different. So the readout signals include four amplitudes for each length of recording marks. The experimental results of readout signal for 7T level 0, level 1, level 2 and level 3 are shown in Fig.6(b).

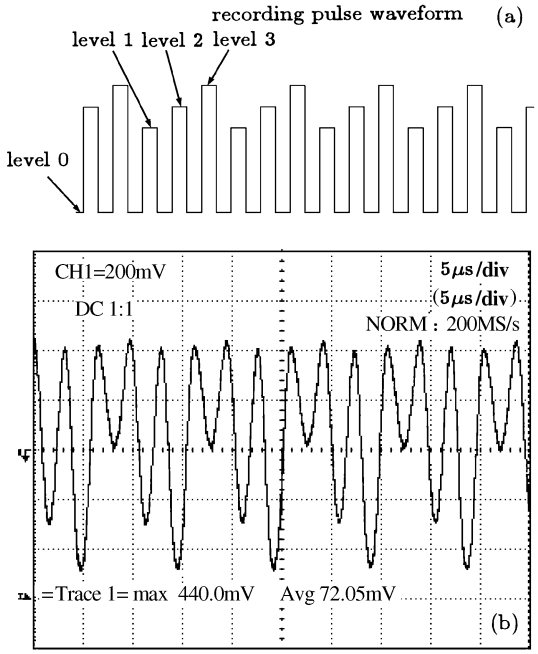


Fig.6. Recorded and readout signals. (a) Write pulse sequence corresponding to recording marks; (b) Readout signals of 4-level RLL modulation (7T).

In ML recording, Sigma to Dynamic Range (SDR) has been proposed for the evaluation of the signal quality.[9,10] In our experiment, the average SDR of the 4L-RLL readout signal is 2.87%. Because the same type of Reed-Solomon product error correction code as DVD is employed in ML RLL read-only discs, the raw bit error rate (BER) before carrying out the error correction must be restricted to 10^{-4}. When we adopt the partial-response maximum-likelihood (PRML) signal process to increase the accuracy of reading the multilevel signal in our experiment, the BER can be kept to less than 10^{-4}.[11]

According to the mechanical reaction of photoresist during exposing and developing, when we change the light intensity irradiating on the positive photoresist, the recording mark profile can be remarkably different with all the other conditions unchanged, including optical equipment, photoresist parameters, exposing, developing and injection molding. The different level reflective signals can be detected by subsequent readout system.

4. Conclusions

The recording density and transfer rate can be obviously increased by applying ML technology. Experimental results indicate that 8-level recording is feasible in read-only disc, and the capacity is estimated to reach 20GB in a {2, 10} 8L-RLL disc without any changes on optical or mechanical units in manufacture. It is a promising method of high-density read-only optical recording in practical application.

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