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A novel methodology for multistate optical storage

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Abstract

A novel multistate storage methodology suitable for 'Read only'-type optical memories is proposed and demonstrated using a simple microstructural design for PbTe thin films. This approach facilitates enhanced storage capacity through multivalued logic. The PbTe films are found to exhibit four different optical states.

Keywords: Optical storage, multivalued operation, multivalued logic, 'Read-only memories', thin films, microstructural engineering.

1. Introduction

Modern computing/communication equipment utilises removable mass storage media either as external memories for personal computers or as a means to develop/distribute economically mammoth software packages. The optical approach for these devices offers significant resolution, speed and compact storage advantages over other magnetic counterparts. A variety of optical materials and 'light–matter interaction processes' such as ablation, laser-assisted phase, topography, chemical or structural modifications, electro-optic, magneto-optic, photodichroic, photo-chromic, photorefractive phenomena have been investigated for optical storage applications[1,2]. Though the literature cites a wide variety of materials and methodologies, the search for new materials and matching interactive processes continues, seeking improvements in storage capacity, larger optical perturbation per unit excitation and simpler experimental procedures to facilitate flexible device engineering. In the present communication a novel recording methodology suitable for removable mass storage optical read-only memory (ROM) is proposed. The methodology is expected to enhance the information capacity of the storage medium and is based on multilevel logic.

The technology of write once and read many times (WORM) type of memory devices is based on burning a series of pits in thin films by irradiation with a laser beam. The pit is identified by a local change in the optical properties of the thin films like reflectivity or absorption. The signals obtained from each pixel are collected into a group called WORD. The information content of the WORD depends upon the radix of the elemental signal and its size. The coding of information in all these devices is invariably done in a binary fashion (radix of 2). The current approaches to increase the storage density include minimisation of the physical size of the pixel and packing the pixels at closer spacing using exotic techniques based on 'near-field' optics, persistent spectral hole burning, 3-D storage, shorter wavelength for write beam, holographic materials, etc.

2. Optical storage *via* multivalued logic

The information capacity of the WORD can be enhanced by changing its radix from 2 to a higher value. Information coding of the WORDs with a radix larger than 2 is often referred to as multivalued logic. In the context of optical storage, this translates to engineering a medium in which the optical character of a pixel can be conditioned into more than two discretely identifiable optical states by controlling the power of the write-laser beam. For a given pixel size and spacing in the storage medium, this approach facilitates higher information capacity than is possible with binary code.

3. Proposed writing methodology

An optical material with appropriate absorption characteristics at the writing laser wavelength is first prepared in thin film form. Binary pits in such media can be burned using laser-assisted heating. In general, as long as laser heating causes some permanent change in the optical properties of the medium (not necessarily hole opening) it can be used as recording mechanism. The burned and unburned areas with different optical character are used to represent binary information. The laser energy required to evaporate completely the volume of pixel depends upon the choice of the material for the medium and corresponds to the highest write laser energy to burn such binary information.

The information storage *via* multivalued logic can be implemented if the optical character of the irradiated region can be set into additional states at write beam energy levels below the maximum required to completely evaporate the volume pixel. Hypothetically, such a situation can be realised if the medium chosen for the thin film exhibits any one of the following two characteristics. The material must be capable of undergoing laser power-dependent transformation to discretely identifiable selective phases. Each of these phases must have its own identifiable optical character and the irradiation conditions associated with them must be well separated in power level. The second category is that the medium must be a multiphase mixture with each of the phases having a different response to laser irradiation with associated optical character.

The former approach was tried by Chao *et al.*[3] using lead oxide thin films. The films have been reported to undergo optically identifiable multiple phases upon laser irradiation. The transformation however required long exposures ranging from a few milliseconds to seconds under controlled conditions making them unacceptable for high-speed storage devices.

4. Microstructure for the storage medium—Design and engineering

The present work concerns with the implementation of multivalued logic using the media containing multiple phases. A microstructural design for the storage medium is proposed to mimic the character of multiphase mixture. The geometric features of the

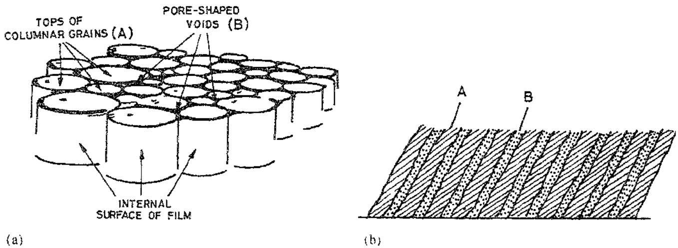


FIG. 1. Proposed microstructure for the storage medium: (a) stereoscopic view, and (b) cross-sectional view.

proposed microstructure for the medium are shown schematically in Fig. 1. The overall medium can be considered as a mixture of two different phases marked as A and B, respectively. These two phases may correspond to the same material differing in the packing density or materials of different chemical composition. The medium with such a microstructure can exhibit multiple optical states if these two regions respond differently to laser irradiation. The resolution and the contrast characteristics of reactions can also be expected to improve with decreasing spatial extent of the regions marked A and B (a few tens of Angstroms each) and increasing difference in laser-specific properties associated with regions A and B.

In the present work, regions A and B of the microstructure correspond to the same material but differ considerably in the associated packing density. Region A is described as rod-like columns with a large packing density while B corresponds to low packing density. The storage medium with such varying packing density is expected to exhibit multistate character when subjected to laser irradiation. The density deficit associated with the loosely packed regions gives rise to low thermal conductivity relative to rod-like regions. When such films are subjected to laser irradiation, the spatial difference in packing density is expected to manifest in a larger temperature rise in the loosely packed regions without affecting the dense regions. The thermal processes that are specific to dense and loosely packed regions can be separated in laser power thereby leading to multiple optical states.

5. Experimental observations and results

It is known for a long time that vapour-deposited thin films of several materials exhibit columnar microstructure characterised by fluctuating packing density across the film. The microstructure of these films resembles closely the proposed design when the ratio of the substrate temperature to the melting temperature of the evaporant is less than 0.45[4]. However, such microstructure cannot be used directly for this purpose. The low-density region is normally about 5 to 10% of the total volume and is practically devoid of appreciable material. The desired microstructure for the storage media requires that regions A and B should have nearly the same volume. Further, region B should have sufficiently large quantum of material. Practical realisation of such a microstructure poses several problems. A structure close to the required can be obtained by depositing the material *via* oblique deposition. Earlier investigations indicate that transient heating gives rise to high reflectance/transmittance contrast with low writing energy in such films[5].

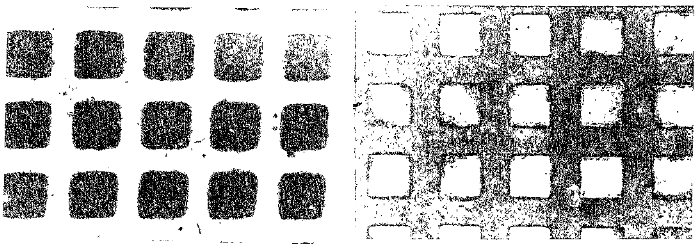
For demonstration of multistate character of laser writing in storage media containing the proposed microstructure, the thin films are prepared using oblique deposition technique. PbTe thin films of 300 nm are deposited on clean microscopic glass slides in a vacuum of 10^{-5} torr. The films are deposited at an angle of 80° for maximum benefit of oblique angle deposition. A free-running Nd:YAG laser with a pulse length of 300 ms is used for irradiating the films. The absorption coefficient of the film at the laser wavelength is estimated to be $>10^5$ cm^{-1}. The bandgap of the PbTe is 0.32 eV and the films will be totally opaque when deposited normally. However, for oblique deposition conditions, the films exhibit partial transmittance in the visible region. Due to finite transmittance at the writing laser wavelength, the reactions of the films are expected to be homogeneous in the volume of the irradiated region. The optical transformations upon irradiation are studied by optical microscopy while microstructural transformations are analysed by electron microscopy.

The experimental observations on the laser-writing characteristics in the proposed medium are as under. The as-deposited PbTe thin films transmit nearly 15% at the wavelength of the reading laser beam. The unburned region constitutes the first optical state for information coding. The PbTe film undergoes topographical changes in microstructure when the thermal processes are dominant in the low density region. As a result, the loosely packed regions undergo a density transformation giving rise to an opaque optical character to the irradiated region. The energy required to set medium into this state over an area of 1×1 µm is of the order of 2 to 3 nJ at a power density of 0.02 mW/μm^2. This opaque state corresponds to the second optical state of the storage medium. When the power density is further increased by a factor 1.5, the dense regions of the film undergo transformations leading to diffusely scattering character in the irradiated region. This optical character corresponds to the third optical state of the medium. Studies based on electron microscopy revealed that the dense rod-like regions undergo chemical and ablative transformations during this state. Finally, when the laser power is marginally increased further over this level, the hole burning *via* ablation resulted giving rise to complete specular transmittance. This corresponds to the fourth optical state.

The optical character of the irradiated region in PbTe films corresponding to the opaque and the scattering optical states is shown in Fig. 2.

6. Conclusions

From these observations it is clear that the thin films of PbTe, when deposited obliquely, facilitate information writing *via* multistate approach. For the chosen methodology for the microstructure engineering, the films had four different optical states each of them characterised by a discretely identified laser-power level. This clearly indicates that the



(a) (b)

FIG. 2 Additional optical states, due to proposed microstructure: (a) opaque state, and (b) diffusely scattering state.

PbTe films can be used as storage medium for implementing multivalued logic with a radix of 4. Such a logic with larger radix of 4 can be integrated easily with the majority of the present-day communication equipment which primarily works with binary signals. Higher radix associated with these multistate media can be of immense use for performance enhancement of the future communication systems.

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