Lithographic Fabrication of Multi-Layered Optical Data Storage

Adam C. Urness, Michael C. Cole, Robert R. McLeod
Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO 80309
Urness@colorado.edu

Abstract— We present a new fabrication method for multi-layer ROM. Individual layers of an initially-liquid holographic photopolymer are photo-patterned via mask projection and post-cured to a solid. The process is repeated to efficiently print high-density disks.

Keywords- multi-layer ROM, Diffusion Driven Photopolymers, Liquid Deposition Photolithography

I. INTRODUCTION

Over the past 15 years there has been a considerable amount of research done on multilayer drives to reach terabyte densities. Bits are written on layers separated by spacer layers so the data can be read through reflection, a similar process to DVD and BD, extended to multiple layers [1,2]. However, optical absorption and reflection of each independent layer limits the total number of layers that can be addressed. To go much beyond 10 layers typically involves finding ways to break this limit. One approach is to electrochemically alter the absorption or reflection of the layer being addressed, leaving the others nearly transparent [3]. This layer selection recordable (LSR) disk requires electrical addressing of a complex multilayer disk but improves the absorption versus depth limitation. The stacked volumetric optical disk (SVOD) is an optical floppy disk with 10 or more micron layers held in a single cartridge [4]. Single layers are pulled from the stack for reading and writing and reinserted when finished. The method avoids the need for optical access to variable depths and variable spherical aberration, but switching through the different layers within the cartridge is complex.

These “switchable” approaches aim to overcome the inherent limits of fixed multi-layer reflective ROM disks. For high layer count, this traditional approach is both expensive, due to the fabrication of the multilayer disks, and constrained in the number of layers the system can support, because the transmission of the system eventually drops below the noise floor if enough layers are added. A potential solution to both these problems is to use a change in refractive index to encode the data instead of absorption.

Current holographic data storage systems use a change in refractive index to encode the data by employing a page based architecture, where the Fourier transform of a data page is interfered in the photopolymer media with a plane wave reference beam. The gratings incident on the media self develop through diffusion of monomer, creating a density increase and therefore higher index in the exposed regions. High data density is achieved through angle multiplexing and polytopic multiplexing of the holograms written [5]. While HDS systems have shown large capacity and improved performance over previous techniques, the drive architecture is complex. This motivates a simpler solution such as writing micro holograms in multiple layers of the same type of photopolymer as HDS [6]. However, SNR scaling and phase aberration limits [7] make scaling to many layers difficult.

Here we demonstrate a new material and fabrication scheme that leverages semiconductor lithography technologies for multi-layer ROM disks that avoid these difficulties.

II. FABRICATION METHOD

Figure 1 shows a simplified version of the fabrication system. Layers are created sequentially by lowering the previously-deposited material and simultaneous injection of pre-mixed UV sensitive liquid precursors of a self-developing diffusion photopolymer. The deposited material is automatically planarized by a non-contact PDMS mold. The new liquid layer is then patterned by 2D mask projection lithography. The pattern, formed of traditional pits and lands, self-develops as an index structure within just the thin, sensitive layer. After the diffusion has completed, the material is optically flood-cured to a desensitized solid. The platform lowers, the next fluid layer is injected and the process repeats.

The key innovation that allows short fabrication time of mm thick ROMs and the liquid layer processing is an inhibited liquid monomer layer adjacent to the PDMS mold [8]. The inhibited liquid monomer layer provides both a short diffusion path axially for monomer to diffuse into transverse structures and automatic planarization of new liquid layers as they are injected into the exposure region. The inhibited liquid layer is
created by diffusion a radical inhibitor from the PDMS into the exposure region.

To demonstrate the capabilities of the method a one micron thick CU buffalo pattern was written between 2 mm of un-patterned polymer. An illustration of the part and system is shown in figure 2b and a photo of the fabricated 4mm thick part is shown in figure 2a. The phase micrograph of the fabricated part is shown in figure 2c.

![Figure 2](image2.png)

**Figure 2.** Layout of device fabrication using the fabrication method. (a) Photo of part printed in the system. c, Deposition chamber layout where a 2D mask has been projected onto a single thin layer which has been encapsulated by additional non-patterned layers. (c) Phase micrograph of part shown in (b)

To demonstrate its multiple layer capabilities a part similar to the one shown in figure 2b was fabricated with an additional written layer separated by an un-patterned 8 um spacer layer. Figure 3a shows a phase-contrast micrograph of a three-micron thick CU buffalo pattern followed by a three-micron CU seal pattern which experienced a 1.8 times longer exposure. The reduction of sensitivity is similar to behavior seen from HDS photopolymers when multiple pages are written. This can be compensated for by using scheduling [9] as we have done here.

![Figure 3](image3.png)

**Figure 3.** Phase micrograph images of index structures written with the system. (a) two sequentially written 3um layers of the buffalo, written first, and the CU seal, written second, where the exposure time is increased by 1.8 times on the 2nd layer to compensate for the desensitization. (b) 1um pitch hologram demonstrating sub-micron resolution transversely

To demonstrate the achievable transverse resolution in the material a one micron pitch hologram using two beam imperfection at 364 um was written in a thin layer similar to the part shown in fig 2b. The phase micrograph of the one-micron pitch hologram is shown in figure 3b.

![Figure 4](image4.png)

**Figure 4.** Reaction/diffusion kinetics of ODS photopolymer used. (a) Material in layer before exposure. (b) Half of the field is exposed causing polymerization in those areas. (c) Diffusion of writing monomer in polymerized region. (d) Entire field is exposed causing polymerization of entire layer

To extend this fabrication method to ODS a layer of bits with BD resolution with sharp boundaries would be written in the same fashion as I have written the University of Colorado school logos. A spacer layer for confocal separation of data would then be created, and the process would be repeated for subsequent bit patterns until the desired density and thickness were achieved.

### III. Optical Data Storage Material

To increase the dynamic range of the index contrast in our storage medium, we have developed a photopolymer in which two monomers, isocyanateoethyl methacrylate and tribromo phenyl acrylate, have a large diffusivity and index contrast difference relative to each other. The isocyanateoethyl methacrylate, known as the matrix material, has a large molecular weight and therefore a small diffusivity. The tribromo phenyl acrylate, known as the writing monomer, has a small molecular weight and therefore a large diffusivity and a larger refractive index than the matrix monomer. The writing monomer will, therefore, diffuse into a monomer depleted area orders of magnitude faster than the matrix monomer, leading to a higher concentration of the writing monomer in the region. Since the writing monomer has a much larger refractive index than the matrix material a substantial index change will occur in the previous depleted region. Taking into account concentrations for the different monomers and there index relative to each other we estimate the maximum index contrast is .01. This material is similar to two-component HDS materials [10] except we photo cure both matrix and writing monomer using same the wavelength and initiator.

The diffusion and reaction kinetics of the material for a common exposure are shown in figure 4. The matrix material is represented by two red circles connected by a line showing that each matrix monomer has two functional groups. The writing monomer is represented by a single blue triangle showing it has a single functional group.
After the liquid monomers are injected into the system as described in previous sections, but before exposure, there is a uniform amount of writing and matrix monomer which is free to move within the liquid layer, shown in figure 4a. When the exposure begins polymer chains form creating a solidified polymer network in the exposed region as shown in figure 4b. In the unexposed region no polymerization has occurred and the monomers are still free to move, however only the writing monomer, due to its high diffusivity, is able to diffuse into the polymerized region as shown in figure 4c. After the mass transport of writing monomer has concluded the entire area within the layer is exposed, polymerizing the entire layer as shown in figure 4d. However on the right side of the dashed line where the original exposure occurred, shown in figure 4b, there is a higher density of writing monomer. Not only does the exposed region have a higher density than the unexposed, but the higher density is of material that has significantly higher refractive index.

IV. DRIVE IMPLEMENTATION

A. Write Implementation

The fabrication method is most compatible with multiple layered ROM where each layer is written and developed using the method described in section II. The key advantage to the proposed method is that many layers are easily fabricated into a monolithic polymer disk. We have not yet optimized the system for the high throughput needed in a commercial environment, however, fabrication times are already quite competitive with WORM demonstrations of 3D data storage. Scaling from the demonstration geometries and materials above and assuming the same writable transverse area and resolution as BD, the required write and development time for a single layer containing 25 GB is approximately 50 seconds. The write time is therefore 500MB/s, meaning a TB could be written in 2000 seconds, which is approximately half an hour. A 2.5 Terabyte drive could be written in just over an hour and would require approximately a millimeter thick disk.

B. Read Implementation

The simplest read-channel implementation is confocal reflection, similar to micro-holographic and other coherent multi-layer schemes. This requires sharp index boundaries at each layer [11]. The separate deposition of each layer and the intermediate spacer layers should provide this boundary. An alternative which has somewhat higher drive complexity but reduced constraints on the disk fabrication is to read in transmission and detect data through deflection caused by transverse index gradients. We have shown [12] that this system has depth-sectioning like confocal reflection but with the distinct advantage that no pinhole is required. Since aligning and maintaining this part has challenging tolerances, this is a potentially attractive alternative read geometry.

V. CONCLUSIONS

We have demonstrated a new fabrication technique for fabrication of multilayered optical data storage disks. Mask projection lithography enables transfer rates of 500 MB/s and fine layer spacing enables high areal density. Initial results indicate that multi TB disks should be possible in a single mm-thick disk which could be written with existing materials in approximately one hour.

REFERENCES