Digital thin-film color optical memory

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A promising optical memory device called digital thin-film (DTF) color optical memory is presented. The DTF optical memory utilizes localized regions of varying thickness to adjust the spectral characteristic of reflected light from a broad band source. The DTF structure has been fabricated by Ga^+ focused ion beam milling on thermally grown silicon dioxide on Si to prove the concept. A charge-coupled device array is used as the optical detector for the readout of the stored data. The reflected light image of the DTF memory reveals easily discriminated color levels and proves the suitability of using optical means to extract the stored data. DTF optical memory structures with 16 physical levels or 4 bits/pixel have been fabricated providing an equivalent storage density in excess of 5 Gb/in.^{2} © *2001 American Institute of Physics.*
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In recent years, the demand for data storage has accompanied the dramatic advances in computing and communication technology. The need for high capacity optical memory has lead to research in optical materials, media structures, and system concepts. Optical materials and effects being investigated include fluorescent materials,[1] dyes,[2,3] photopolymers,[4] the electron-trapping effect,[5] photorefractive materials,[6] the magneto-optical effect,[7] the phase-change effect, persistent spectral hole burning,[8] photobleaching polymers,[9] two-photon absorption[10,11] materials. Media structure and system research directions include holography,[12] the solid-immersion lens,[13] three dimensional multilayer, near-field scanning optical microscopy memory[14–17] and dielectric mirrors,[18] etc.

In this article, we introduce a concept for optical memory devices utilizing reflection of a broad band light source from the digital thin film (DTF) structure shown in Fig. 1. The basic physics is very simple—interference and superposition of light at multiple wavelengths. The phenomenon of interference of laser light at a single wavelength is used in CD ROM, where interference of light waves reflected from a pit and from the laterally adjacent area create constructive or destructive interference which is interpreted as ''1'' or ''0''. In the DTF structure, the interference process occurs vertically between the two interfaces of the dielectric thin film.[19] This reduces the effective memory element area by removing the need for the adjacent area of a pit as required in CD ROM. The DTF device also takes advantage of the multiple wavelengths contained in broad band light. By using a broad band light source, the reflected output is the superposition of many interference results of different wavelengths. The final result of these properties is to create an effective color for each bit location as a function of film thickness, incident light profile, and the spectral responsivity of the detector. In this way, DTF structures create multiple memory bit storage in the third dimension by using pixel colors, as compared to only two states for CD ROM. In this context, one can think of CD ROM as data storage in black and white while DTF stores data in color.

To prove this concept, we have fabricated DTF optical memory arrays on silicon dioxide thin films (800 nm) thermally grown on silicon substrates. The film roughness measured using atomic force microscopy (AFM) was evaluated to be 1–2 nm. Arrays of bit patterns were fabricated using focused ion beam (FIB) micromilling. The FIB utilized Ga^+ ions accelerated to an energy of 30 keV. The individual data location, or pixel, was varied in size from ~0.5 to 2 μm. Different milling depths are achieved by varying the Ga^+ dose. The dimensions of the array are characterized by AFM to determine pixel area and depth. An example of a staircase-style milling profile is shown in Fig. 2. The nominal lateral dimension of all pixels is 954 nm. The depth of each pixel takes on one of 16 levels, from zero to nearly 800 nm. This is achieved by changing the dose from 0.35 nC/μm^2 for level 1 to 5.2 nC/μm^2 for level 15. The milling rate is approximately 310 μm/s (or 0.144 μm^3/s) using 1 nA beam current. The milling depth is seen to increase linearly with dose for levels up to 12, with apparent sublinear dependence from

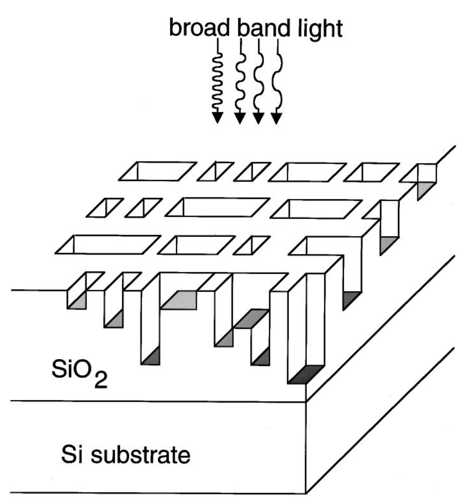

FIG. 1. Diagram of DTF optical memory device structure utilizing an SiO_2 layer grown on a Si substrate. The SiO_2 film is micromilled to different discrete depth levels using FIB.

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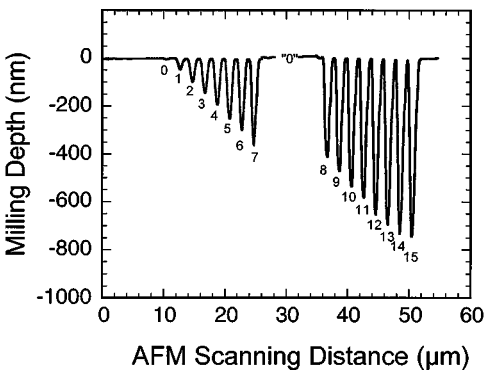

FIG. 2. AFM line-scan profile of a DTF device. The profile shows 16 discrete levels produced by FIB milling. The horizontal pixel pitch in this profile is approximately 1 μm.

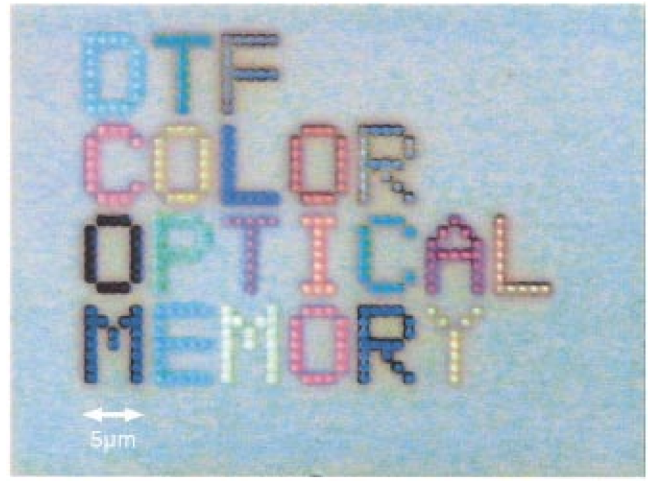

FIG. 4. (Color) Color reflected light photograph of a fabricated DTF memory structure taken using a 100X objective lens and a CCD camera. The 16 depth levels produced 16 distinct colors.

level 12 to 15. This sublinear characteristic is probably mostly a function of the difficulty of obtaining accurate depth measurement with AFM when the aspect ratio reaches a certain value.

Examples of FIB-fabricated DTF arrays are shown in Fig. 3. The array in Fig. 3(a) contains a set of data chosen such that their image forms letters milled to various levels. The pixel-to-pixel pitch is 700 nm and the depth has 16 thickness levels, or 4 bit color depth. The resulting bit density is greater than 5 Gbits per in.^{2}, which is more than twice that of current digital versatile disk devices. Figure 3(b) contains an AFM area image of a 16×16 array with a total of 256 different milling levels or an equivalent of 8 bit pixel depth.

The DTF memory device produces vivid colors when examined under an optical microscope. We used a high numerical aperture (0.90) $100\times$ objective lens and an analog charge-coupled device (CCD) camera together with a video frame grabber to capture the reflected light image. The optical image shown in Fig. 4 shows a similar pattern to the AFM image in Fig. 3(a) but with a pixel pitch of $\sim$1 μm. The optical image clearly shows the distinct color of each letter caused by different milling depth (and resulting film thickness). In this array, the total number of film thickness levels is 16, including the unmilled film thickness. The milling depth is randomly assigned to each letter. By properly selecting the incident light profile and detector responsivity for the specific film thickness set, one can enhance color differences between levels and increase the maximum number of colors detectable.

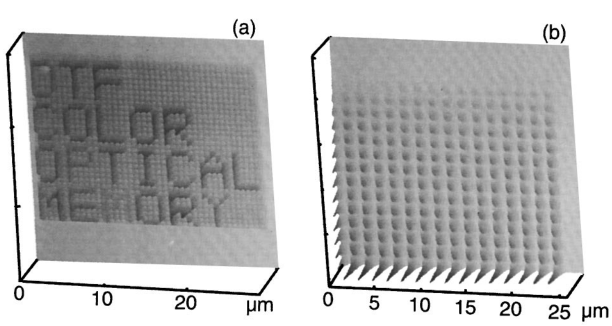

FIG. 3. AFM array images of two DTF structure arrays: (a) 41×31 array with pixel pitch of 700 nm and 16 milling levels; (b) 16×16 array with 256 milling levels.

The bit density capacity of the DTF optical memory depends on several factors: (a) the ability of the FIB to pattern nanometer-scale regions with high precision in all three dimensions; (b) the ability of the read-out system to detect optical signals from these nanometer pixels. The first factor requires significant additional investigation, but it is important to point out that sub-10 nm beam diameters have been reported in FIB system.[20] To reach those very small beam diameters requires a reduced beam current, which in turn increases the writing time. The optical read-out issue will probably necessitate the use of the near-field optical detection approach. For example, Partovi *et al.* have reported[21] the use of a very-small-aperture laser (VSAL) to read 250 nm diameter bits, corresponding to 7.5 Gb/in.^{2} storage density. We envision using this VSAL readout at several different wavelengths sequentially to compute the corresponding ''color'' and thus extract the data from the pixel array.

Using the result presented herein as a stating point, we can extrapolate the storage capacity of future DTF optical memories. If we made the assumption that the aspect ratio (width to depth) of a pixel with maximum depth should be unity in order to capture sufficient reflected light. This is the worst case, since most pixels will have a smaller depth. A calculation for reasonable pixel dimensions of 250 nm width, 250 nm maximum depth, and 3.5 nm minimum step size yields a 6 bit/pixel storage and a storage density of $\sim$60 Gbit/in.^{2} A calculation for aggressive pixel size of 30 nm, but the same 3.5 nm minimum step size, results in 3 bit/pixel storage and $\sim$2 Tbit/in.^{2} density. While not yet proven, these extrapolations clearly show the enormous potential of the DTF approach.

Another important aspect of the DTF memory structure is that it is possible to create microcolor digital pictures directly in the memory device. This property can lead to applications in data security. The color picture formed by the stored data can be recognized quickly under an optical microscope. The image is very difficult to alter and should be able to withstand harsh environments such as extremely high temperatures, exposure to radiation, etc.

In summary, the DTF color optical memory device structure has been introduced. This device utilizes a nontra-

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ditional approach to increase the density of optical memory. A broad band light source is used instead of a laser to read the data. The writing process is performed using FIB micromilling of an SiO_2 film on a Si substrate. The result yields multiple color levels due to light interference effects in dielectric film regions with varying thickness. The current memory device reported here has a bit density of ~5 Gb/in.^{2} Future extensions of this approach have the potential reach a density of 2 Tb/in.^{2}

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