Optical Thin-Film Structures for Color Analog, and Digital, Long-Term Information Archiving

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Abstract

We have demonstrated the use of selective, reproducible, milling of sub-micron feature sizes by focused ion beam of optical thin film structures made from robust materials for color and B&W, analog and digital image and text archiving. This method has also been used to create diffractive structures with controlled, variable diffraction efficiencies. Modeling of the material optical properties, both pre- and post- milling, has enabled accurate prediction of material reflective, transmissive, and diffractive properties, and has effectively shown that ion implantation effects, such as compositional changes and ion deposition, are of second order importance to the optical behaviour of the thin film system.
Keywords: optical thin film, color analog archiving, focused ion beam, digital archiving, diffractive structure

Introduction

It is known that a focused ion beam (FIB) apparatus can be used to alter selected regions on the surface of a medium, either by ion implantation into the medium, or by milling of the medium, and that the regions of implantation and/or milling can be controlled to within a transverse spatial resolution in the nanometer (10^{-9} meters) range[1,2]. Micro-machining of materials can also be achieved by etch sensitization of the material, i.e. by using the fact that a region implanted with ions will etch at a different rate than the un-implanted region when exposed to strong acid or base solutions[3,4,5]. Furthermore, alteration of the medium by ion implantation has direct consequences to the optical properties (reflectivity, transmissivity, absorption,) of the materials[6]. In addition to material changes caused by implantation with ions, the optical properties of thin films has been well understood for many years[7]. Making use of the properties of optical thin films, it is possible to amplify small changes in optical properties (i.e. index of refraction, physical and optical thickness,) of a material through the interference filtration properties of such optical thin films. Results of these changes can be used to create small regions of selectable color, such as pixels within a picture, as well as spatial structures with pre-selectable diffraction efficiencies.

Basis of the effect

The (FIB) apparatus can be used in at least four modes of operation to alter a medium in a predictable and controllable way to record analog (or continuous) and/or digital (or discrete) images or data:

a) implantation of ions within specified surface regions;
b) implantation within and milling of specified surface regions;
c) implantation within and subsequent chemical etching of specified surface regions;
d) implantation within, milling of, and subsequent chemical etching of specified surface regions.

Methods a) and b) were used to create the samples illustrated in this work.

Data is stored on the medium surface based on the predictable and controllable changes in the surface optical properties (reflectivity, transmissivity and absorption) of the medium; changes in optical properties within a single material can be broken down into the following nine general categories:

1) Changes in optical properties due to material amorphization.
2) Changes in optical properties due to material expansion.
3) Changes in optical properties due to material contraction.
4) Changes in optical properties due to formation of color centers within the material.
5) Changes in optical properties due to formation of micro-clusters within the material.
6) Changes in optical properties due to material ordering (crystallization.)
7) Changes in optical properties due to material doping.
8) Changes in optical properties due to material implantation.
9) Changes in optical properties due to material composition changes.

These changes occur within the implantation depth of the ions into the medium.

The actual realization of these optical changes can be enhanced by the use of optical thin film structures. The basic effect can be illustrated with figure 1:

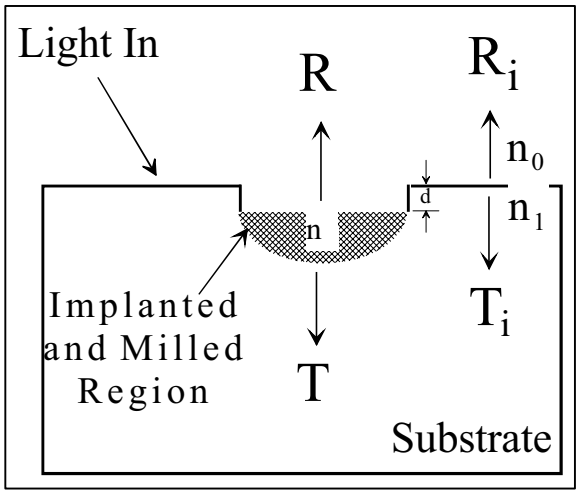

Figure 1: Changes in structure optical properties due to implantation into and milling of a substrate.

In general, descriptions of the changes in optical properties are described in terms of only the *reflectivity* and the *transmissivity* of a material or material structure, because these are the quantities which are observed directly. (The absorption plays a role in both of these quantities.) Furthermore, the optical changes described above entail changes in both the *amplitude* and the *phase* of the reflected and the transmitted light signals. These changes are described in the following equations.
(The following definitions apply to the equations)

$$r_{ab} \quad \frac{n_a \quad n_b}{n_a \quad n_b} \qquad t_{ab} \quad \frac{2n_a}{n_a \quad n_b} \qquad \delta_a \quad i\frac{2\pi n_a l_a}{\lambda_o} \tag{1}$$

In the following equations, the subscripted variables r_{ab} represents the amplitude and phase reflectivity (generally a complex number) at the interface between media "a" and "b," for light traveling from medium "a" into medium "b." Similarly, the variables t_{ab} represent the amplitude and phase transmission for light encountering the interface going from "a" to "b." The *energy* or *intensity* reflectivities and transmissions can be found simply by multiplying these numbers by their complex conjugates. These reflectivity and transmissivity values are calculated in terms of the, generally complex, indices of refraction of the media, "n." The index of refraction in medium "a," for example, is written as "n_a." The reflectivity and the transmissivity of the unaltered structures are listed below as R_i and T_i, respectively. The reflectivity and transmissivity for the altered structures are then listed as R and T , respectively. Finally, the subscript on the right hand side of the equations (e.g. n ,) represents the properties within the region that has been altered by the focused ion beam.

$$R_i \quad r_{01} \qquad\qquad T_i \quad t_{01} \tag{2}$$

$$R \quad r_0 \, e^{i2\pi\frac{2d}{\lambda_o}} \qquad\qquad T \quad t_0 \, e^{i2\pi\frac{d}{\lambda_o}} \tag{3}$$

The equations governing multiple thin films are easily found by replacing the relevant reflectivity of an interface with the reflectivity of the underlying thin film structure.

These optical changes can be used to create individual regions of color (or black or white,) with resolution of these regions limited only by the longest wavelength of light which will be used to read back the stored information and retain the color information. Because the changes in optical properties are controllable and predictable, the reflection and transmission properties can easily be calculated for any given illumination source. In the case of visible light, the useful minimal size of a region, or "resolution," can be as small as 0.7 microns for standard white light microscopy. For shorter wavelength light, this minimal sized region decreases proportionally to the maximum wavelength of light to be used.

Analog Archiving

Method I: Interference Pixels

Using an optical thin film (ranging in thickness between 1/1000 and 100 times the wavelength of light to be used,) coated on a polished, base substrate or optical thin film structure, it is possible to change the optical depth selectively of the surface layer by implantation and milling with the FIB, as illustrated above. Because optical thin film structures act as interference filters, the local changes to the surface layer (including the change in thickness) serve to change the wavelength tuning of the interference filter structure, resulting in color change on reflection or transmission of white light incident on the region.

Figure 2 shows a diagram of a sample created to illustrate the archiving method described with figure 1. Readback of information can occur in both reflection and transmission modes.

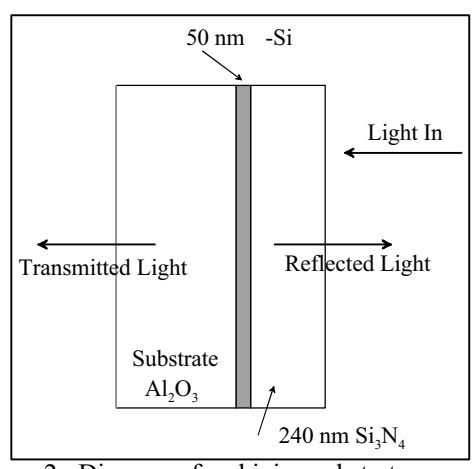

Figure 2: Diagram of archiving substrate.

A substrate of sapphire, Al_2O_3, has been coated with an optical thin film of 50 nanometer thickness -Silicon, and then 240 nanometers of silicon nitride, Si_3N_4. Figure 3 shows the predicted color range under white light illumination for both transmission and reflection perpendicular to the surface for the medium described. Note the color range includes a grey scale that goes from white to black. Figure 4 shows a photograph of a wedge measuring 10 microns on a side, taken through a microscope with light reflected back from the surface. Figure 5 shows an Atomic Force Micrograph (AFM) of the same structure.

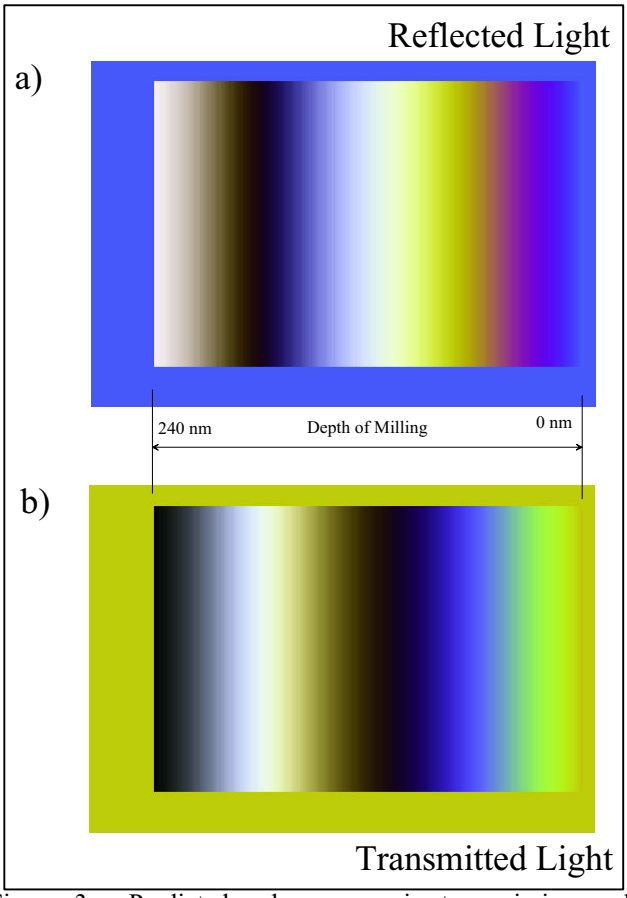

Figure 3: Predicted color ranges in transmission and reflection

Figure 4: Reflected color from a wedge cut in a sample like that of figure 2.

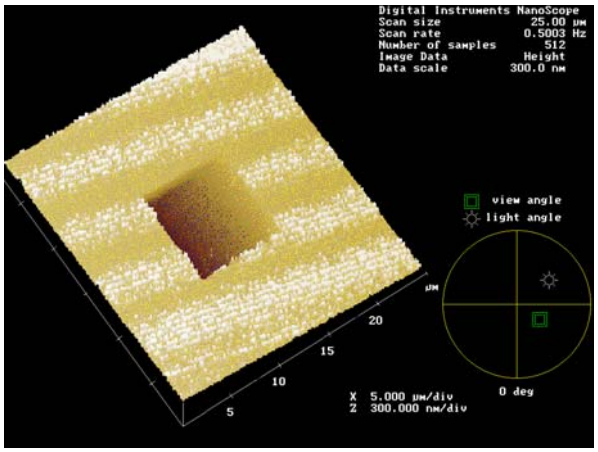

Figure 5: AFM of sample surface.

When used to store color, the smallest pixel must accommodate the longest wavelength in use, e.g. about 0.7 microns for visible light. This limits the pixel size to about 0.5 square microns. When using black and white, or grey scale, images, the reflective or transmissive properties of the surface can be monitored at a single wavelength. Using visible light, the shortest wavelength is about 0.4 microns, leading to effective pixel sizes of 0.16 square microns. Using a UV source of 0.2 microns, the pixel size for a grey scale image is further reduced to 0.04 square microns.

Method II: Diffractive Pixels

Analog storage can also be achieved using diffractive structures. By reducing the silicon nitride layer shown in figure 2 to 65 nanometers, the comparable color range (similar to that shown in figure 3) achieved by milling through the silicon nitride region is relatively insensitive to light color, yielding an effective grayscale. By selectively milling periodic patterns to alter the reflectivity/transmissivity in controllable way, regions that diffract different colors can be created, controllable both in color AND intensity.

A simple illustration of how this can be used for archiving is shown in figure 5. Defining the direction perpendicular to the surface of the storage medium as the "Z" direction, and also as the observation direction, it is possible to create periodic changes (using one of the six methods outlined above) along the X-direction with one period, and periodic changes along the Y-direction with a different period. This "checkerboard" structure can now be illuminated from a fixed set of angles in the X-Z plane (e.g. 40 degrees from perpendicular in either direction) to diffract one spectrum of light due to the periodic structure along the X-direction, and from a fixed set of angles in the Y-Z plane (e.g. 40 degrees from perpendicular in either direction) to diffract another spectrum of light due to the periodic structure along the Y-direction. In this way, a full range of colors, including black and white, can be created in a small region. Furthermore, intensity at each color can also be controlled by adjusting the contrast depth of the periodic variations (whether this is the peak to peak

variation of the phase of the reflected light as a function of position, or the amplitude, or both.)

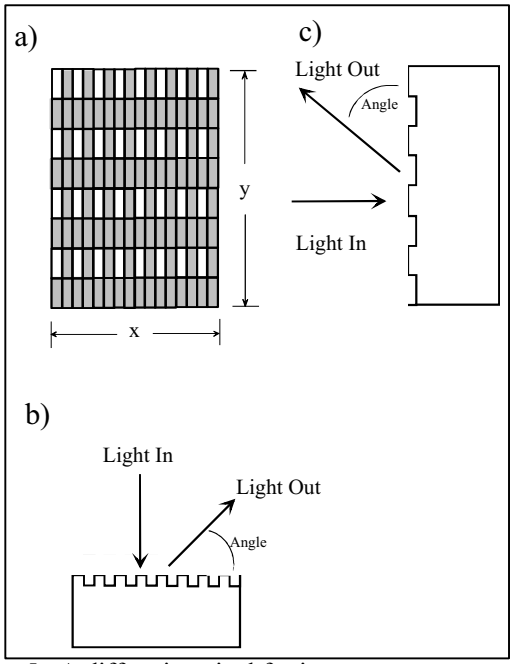

Figure 5: A diffractive pixel for image storage

Pixel sizes of approximately 2.5 microns on a side, or about 6 microns squared, can be achieved with reasonable diffraction efficiencies for use with visible light. Recovery of the image in real color is achieved using a microscope or other, similar, optical viewing apparatus. For black and white storage, visible light could be used monochromatically at 0.4 microns, allowing pixel sizes of 1.2 microns on a side, or 1.5 square microns. For UV illumination, these numbers can be further reduced to a pixel size of 0.7 microns on a side, or 0.5 square microns.

Comparison to State-of-the-Art Analog Image Storage

State-of-the-art analog image archival storage is currently done with photographic film. State-of-the-art resolution is defined by the effective grain size within the film, which defines the minimum "pixel" size for purposes of resolution comparison. For black and white images, the grain size is approximately 3 microns in diameter, giving a pixel area of 10 square microns. For color analog archival storage, this color grain size is on the order of 10 microns, for an effective pixel size of 100 square microns.

Using the two examples outlined above, the relative storage densities for color and black & white archiving are compared in the following table:

Storage Method	Pixel Size (m^2)	Improve Factor
B&W film	10	1
Color Film	100	1
B&W Interference	0.16	60
B&W UV Interference	0.04	250
Color Interference	0.5	200
B&W Diffraction	2.0	5
B&W UV Diffraction	0.5	20
Color Diffraction	6	15

Clearly, both of the archiving methods outlined in this paper represent an advantage in storage density over microfilm. Furthermore, the materials used for the archiving can be made nearly indestructible.

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