Ultrathin Color Filter for Wearable Displays and Multispectral Imaging

Z. Zhan[1], M. DeMarie[1], B. Zhou[2], X. Liu[3], J. Sun[1], and A. H. Titus[4];

[1]Department of Electrical Engineering, University at Buffalo, The State University of New York, Buffalo, NY 14260; [2]KLA-Tencor, Hayward, CA 94545-1815; [3]Lawrence Berkeley National Laboratory, Berkeley, CA 94720; [4]Department of Biomedical Engineering, University at Buffalo, The State University of New York, Buffalo, NY 14260.

Abstract

We present a new approach to making in-pixel color filters for a wearable display such as LCOS (liquid crystal on silicon) or a DLP (digital light processing) system. Unlike current color filters or methods used in these devices, our approach enables Red-Green-Blue (RGB) color images using color filters fabricated using semiconductor ultra-thin film. These filters are less than 100 nm thick, making them better suited to integration with light modulators than traditional pigment-based filters. Additionally, these films are fabricated via e-beam evaporation or RF sputtering, which is compatible with most modern chip manufacturing. In this paper, we present the design concept for these filters, including simulation results that demonstrate improved liquid crystal control when using these filters, demonstrate an example RGB filter array and also present an enhanced structure which could meet requirements of DLP based multispectral imaging. This is the first time the use of these filters is presented for use in liquid crystal based displays and DLP.

Introduction

A traditional color projector system uses three independent panels to produce a Red, Blue and Green (RGB) graph. A complete color image is obtained by combining each of these graphs [1], which requires a specially designed prism and several dichroic filters. The limits of this method are obvious: it is difficult to reduce the overall size due to the number and size of the optical components. In order to reduce the size of projectors, different technologies are required or different imaging techniques are needed. One alternative is based on a sequential imaging method in which red, green, and blue light is displayed sequentially in time [2]. By using a sufficiently fast display rate, the visual persistence phenomenon produces what appears to be a full color image to human viewers. The drawbacks of this method include rainbow striping that occurs at the boundaries between colors, and reports of discomfort [3]. Additionally, the cost of these systems can be high, since higher speed components are needed to achieve fast sequential processing. Another other option is to use mosaic filters [4], which are in-panel red-green-blue (RGB) color filters where a single "pixel" is actually composed of four RGGB subpixels. These color filters are used in almost all modern digital cameras. There also has been work to integrate these color filters into Liquid Crystal on Silicon (LCOS) based projectors [5]. In these systems, the filters are traditional pigment-based (PB) color filters, which is a mature technology and compatible with liquid crystal (LC) panel production. But since the filter is normally more than 0.75µm thick and relatively insulating, when stacked on top of the LC (see **Figure 1** for a schematic representation), the filter can adversely influence the performance of the LC and can limit any attempts to reduce the system size [6].

One approach to reducing the size of projectors is to reduce the size of each pixel (and sub-pixel). However, as reported, the properties of the existing color filters limits the pixel size because of their minimum thickness is quite large and their resistivity is also high. So, any LCOS-compatible replacement for these filters should be extremely thin, have low resistivity (to allow for a higher electric field across the LC, between the bottom driving electrode and top common electrode), as well as be compatible with existing fabrication processes. Additionally, the filters should be reflective and should be able to be processed (or tuned) to achieve the desired colors.

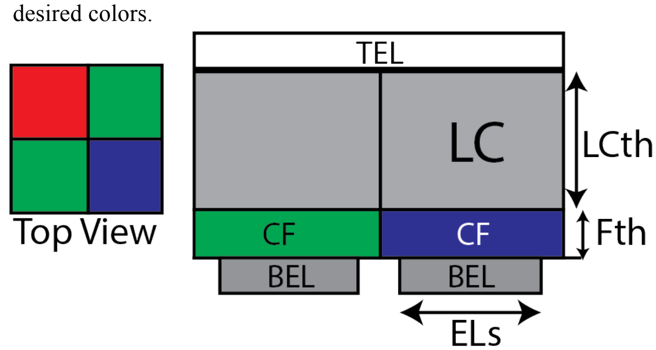

***Figure 1**. Diagram showing the side view of two pixels. A single functional pixel is made of four individual pixels (RGGB). LC = liquid crystal. CF = color filter, TEL=Top (common electrode, BEL=Bottom electrode.*

In this paper, we present a new color imaging technology that is based on ultra-thin film Germanium. These ultra-thin films are well suited to replacing traditional filters in projectors because 1) they can be tuned to get the desired color, 2) they are reflective, 3) they are extremely thin, and 4) they have a low resistivity. By meeting all of these criteria, the ultra-thin film filters can be easily integrated with LCOS devices to create smaller pixels that can enable smaller projectors or higher resolution projectors. In this paper, we describe the properties of these ultra-thin films and show how they can be integrated with LC to create an RGGB pixel. We present simulation results that demonstrate that by combining these ultra-thin films with LCOS, we can achieve a higher electric field across the LC, which will allow for better performance or enable smaller sized pixels. We fabricate an RGB array to demonstrate the optical quality, and then demonstrate via simulations that the concept can be used to create an improved multispectral imaging system.

Thin Film Filters

Optical coatings are widely used to enhance or reduce reflectivity for a wide or narrow range of wavelengths [6]. In general, the coatings are based on optical interference using one or more dielectric/metallic film layers to achieve the desired reflection or absorption property for the wavelengths of interest. However, fabrication of these coatings requires material deposition processes that often are not compatible with mass microelectronic fabrication, and thus increase the cost of the coated devices significantly. Recent research [7] has demonstrated that ultrathin metallic films can produce an ultra-high absorption resonance over a narrow optical spectrum. The absorption spectrum can be adjusted by changing the thickness of only one material (one layer); this greatly simplifies the fabrication process. It was indicated that interference can persist in these ultrathin, highly absorbing films under appropriate conditions, which results in wavelength-specific absorption of the incident light [7]. Starting with gold as a base, the reflectivity of this layer can be engineered by depositing a highly absorbing dielectric layer on it. Due to its high absorption in visible wavelengths, germanium is a good candidate for this dielectric layer. Therefore, gold topped with germanium layers has a broadband optical absorbance characteristic that can be modified by adjusting the film thickness, resulting in the ability to fine-tune the absorption spectra.

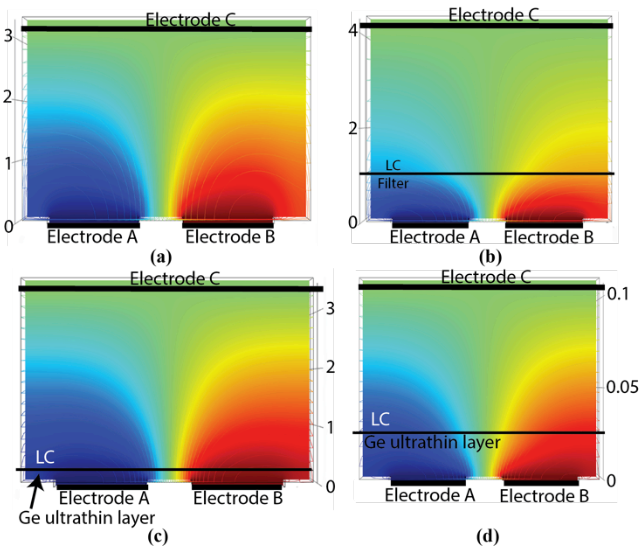

Figure 2. Electric field simulation results for four LC pixel arrangements. a) no filter, b) PB filter, c) ultrathin film color filter with large pixels d) ultrathin film color filter with small pixels.

Pixel simulation and structure comparison: The on/off status of LC is controlled by the electric field across it which is applied between the bottom electrode and top electrode [8]. The stronger the electric field that can be applied across the entire LC layer, the more fully the LC can be switched, so the ratio of on to off (contrast) can be better. In an array of LC pixels, this means each pixel can be distinctively different from its neighbor, improving the overall performance; this is very important when LC arrays are used in a projector.

By using the ultrathin film Ge layer as a filter, it is possible to create better and smaller LC arrays for projectors. In order to demonstrate this, we performed simulations using COMSOL to show the electric field distribution between the bottom and top electrodes across the LC with either the PB filter or ultra-thin film filter. The simulations are performed on a 2×2 pixel matrix emulating a RGGB color pixel arrangement for projectors (see **Figure 2**). The dimensions are all in micrometers, and the x and y axes in each subfigure in **Figure 2** have the same scale. The colors represent voltages from 0 V (blue) to 5 V (green) to 10 V (red). Appropriate electrical parameters are chosen for each layer for simulation, as outlined in Table 1.

Table 1. Parameters used for simulations.

Filter Type ->	(a) No Filter	(b) PB	(c) Ge	(d) Small Ge
Electrode size (ELs)	1.6 μm	1.6 μm	1.6 μm	40 nm
Filter thickess (Fth)	*NA*	1 μm	.2 μm	25 nm
LC thickness (LCth)	3 μm	3 μm	3 μm	75 nm
Filter εr	*NA*	3.9	16	16
LC εr parallel	10	10	10	10
LC εr perpend.	3.1	3.1	3.1	3.1

Figure 2(a) shows the result for no filter, so the LC is the only material between the lower controlling electrode and upper common electrode. In **Figure 2**(b), the electric field decays very quickly in the PB layer, resulting in a small voltage across the LC, which implies that a higher total voltage is needed to achieve the same control as for a no filter arrangement. As shown in **Figure 2**(c) and (d), the ultrathin film filter enables a much higher field strength across the LC because the Ge layer has a much higher conductivity and permittivity than the PB filter that is almost an insulator (resistivity of 10^{12} Ohm-m), and because the Ge layer is extremely thin. Indeed, the field distribution across the LC in the ultrathin film pixels is nearly identical to the no filter case. **Figure 2**(d) is included to show the results for a much smaller pixel area (electrode size of 40nm x 40nm), and thus a much smaller volume. This shows that smaller sized pixels can be created to either increase pixel density or decrease the array dimensions while not affecting performance. The primary concern with reducing pixel area without reducing the layer thicknesses (height) is that cross talk between neighboring pixels increases, which reduces the image quality. However, the reduction of area and corresponding reduction in LC volume, as exemplified in the small ultrathin layer pixel, means that the necessary electric field distribution across the LC can be maintained, so cross talk does not increase. This cannot be done with the PB filters because of the relative thicknesses of the layers. The challenge is to create a LC that can provide sufficient switching contrast at thicknesses of less than 100 nm. It is possible to make a high-resolution projector device while keeping the total device size small. For example, a 1μm square

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pitch size (which would is the limit for LC today) in a 4K HD display size would only be 8.19mm x 4.32mm, which is even smaller than an image sensor for cellphones. However, if the size becomes too small, it may reach the half wavelength limit for people to recognize color.

Fabrication and Testing

To demonstrate the ability to make the ultrathin film filter arrays, we fabricated a number of different patterns using Ge on Au, although other materials may be used. The Au and Ge films are deposited using an electron beam evaporator. Starting with a standard glass microscope slide, a 5nm Ti adhesion layer is deposited first, followed by a 100 nm Au film. Next, the Ge film is deposited to achieve the thicknesses needed to produce the desired reflected colors. A 10 nm thick layer results in red, a 15nm layer produces blue and a 25nm layer produces green. The colors can be adjusted by varying the thicknesses slightly. A picture of one slide with various patterns is shown in **Figure 3**a. The matrix and pinwheel patterns are made by combining standard photolithography with the deposition process. The RGB array patterns have feature sizes range from 20 µm x 20 µm to 1 mm x 1mm, but smaller sizes can be achieved easily using conventional CMOS lithography processes. **Figure 3**b shows an enlarged view of the 20 µm x 20 µm RGB matrix illuminated with a Halogen lamp.

To obtain a quantitative measurement of the reflected light from the RGB pixels, we used the Ocean Optics USB4000-VIS-NIR Fiber Optic Spectrometer to obtain a reflection spectrum, shown in **Figure 4**, illuminated with a CREE-R2 LED (white). The peaks indicate the color of the pixel, and the spectrum for these compared favorably to those obtained from existing devices, such as the iPad and iPhone4.

(a) **(b)**

***Figure 3**. (a) Standard glass microscope slide with RGB patterns. (b) Close-up of smallest RGB pattern (c)*

Compared with the mirasol display from Qualcomm, which is an interferometric-based approach, this thin film method has several advantages. First, the mirasol display size is limited by the MEMS structure. It is not as complicated as the PLD, but it will be limited to the micron-level. Second, the switching speed is limited, which not only limits the frame rate, but also makes it difficult to produce as many colors as today's displays (the mirasol display achieves more colors using a larger area and more pixels to produce a single color). Third, the mirasol display is hard to adjust (tune the color response) as it is interferometric-based while material absorption provides more flexibility in tuning in our proposed device. So mirasol display is better suited to more static displays, such as ebook readers, because it reflects more light while consuming less power, while our device is more suited to dynamic, rapidly changing displays on devices such as Google glass or a projector on a cellphone.

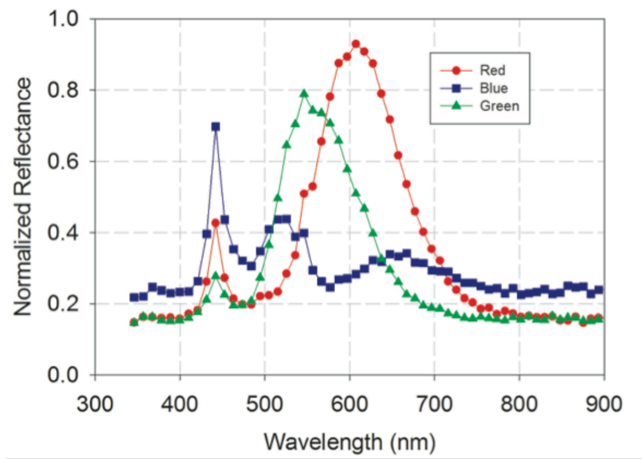

***Figure 4**. Reflection spectra for the red, green and blue pixels.*

Germanium on metal structure is preferred for an RGB system due to its large and wideband absorbance; this makes it easier to create a true RGB color array using only an additional broadband filter or true white light source. However, in multispectral imaging applications, it is a disadvantage, as these systems desire a narrow spectrum. To meet this need, we created a modified structure of Si+TiO_2+Al as shown in the inset of **Figure 5.** The Si has weaker absorption as compared to Ge, which can provide a narrower absorption spectrum (for thicknesses ranging from 20nm to 75nm). This is combined with TiO_2 (approximately 65nm thick) which has a high refractive index to further narrow the absorbance as shown in **Figure 5.** This structure is compatible with DLP as the mirrors in DLP are aluminum, so only two additional deposition layers are needed. For typical multispectral imaging systems, an adjustable grating is used to provide the wavelength selectivity, but these limit the beam structure and overall system size since then cross-talk can be a problem in grating-based systems [9]. The proposed structure can enable very fine wavelength selection and eliminate the need for the grating. An additional benefit of this type of color filter is that the filter array can be any pattern and size, while a linear grating system requires additional beam-shaping optics to minimize distortion. For completeness, we subtract the reflectance values shown in **Figure 5** from 1 (by assuming a white perfectly reflective background) to show the intensity for each individual wavelength, see **Figure 6.**

Conclusion

We demonstrate the ability to make highly reflective color filters that allow them to be used in small, lightweight projectors or wearable display glasses (such as Google Glass) and multispectral imaging. The fabricated samples were used to obtain reflection spectra and simulations show that the thin, low resistivity filter layers can improve the LC performance. Additionally, after four months, there is no obvious change (fade) in the colors. Since the fabrication processes used to make the films are CMOS-compatible, production of the filters can be easily integrated into projector chip fabrication, which will greatly reduce costs.

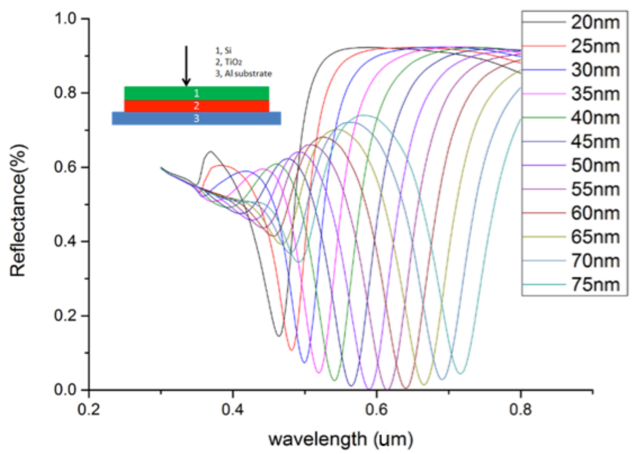

Figure 5. *Simulation of reflection spectra for Si-TiO_2-Al structure for a range of silicon thicknesses.*

One issue for packaging for a commercial device is that a protection layer will be needed, as even for Ge and Au will peel off in strong ultrasonic environment due to the ultrathin thicknesses. Also the choice of the protection layer is important because the interaction between top layers might change the optical properties like absorbance and phase. And, the addition of the protection layer will increase costs due to the need to deposit the extra layers.

Future work includes using finer masks to achieve smaller grid patterns down to 1 um or smaller on a side, developing a deposition recipe to optimize the spectra obtained, and development of a snapshot multispectral imager based on this color filter design.

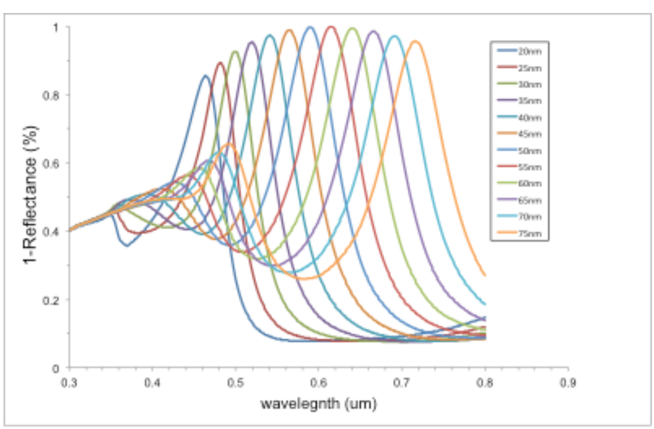

Figure 6. *Compensated data of reflection spectra for Si-TiO2-Al structure from* ***Figure 5****.*

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Author Biographies

Zhiyong Zhan *received his B.S. degree in Engineering of Automation Control from Southeast University, China in 2007 and M.S. degree in Electrical Engineering from the University at Buffalo. Currently, he is a Ph.D. Candidate in Department of Electrical Engineering at the University at Buffalo. His research interest areas include color recognition chips, CMOS integrated chemical and biological sensors and self-powered VLSI designs.*

Bin Zhou *received the BS degree in Electrical Engineering from Shan Dong University of China (2007), an MS degree in communication and information technology from Bremen University of Germany (2009) and PhD in Electrical Engineering from the University at Buffalo (2013). Since then he works as Development Engineer at the Electron Beam Division of KLA-Tencor in San Francisco Bay Area, California. His work has focused on organic polymer/nanocrystal photovoltaics, thin film optoelectronics, semiconductor inspection and review tools.*

Xin Liu *received his BS in chemical engineering from Tianjin University (China, 2008) and his PhD in chemical engineering from the University at Buffalo, the State University of New York (2014). Now he is a postdoc working at Lawrence Berkeley National Laboratory. His work briefly focuses on nanotechnology, optoelectronics and nanoelectronics.*

Mark DeMarie *received his BS (2011) and MS (2013) in Electrical Engineering from the State University of New York at Buffalo. He is currently continuing on towards his Ph.D. focusing on sensor development and analog circuitry. Studies thus far have included BDJ color light sensing with IC mask level fabrications pressure sensor systems with PCB board designs.*

Albert H. Titus *received his B.S. and M.S. in Electrical Engineering from the University at Buffalo in 1989 and 1991, respectively. He earned his Ph.D. from the Georgia Institute of Technology in 1997. He is now a Professor at the University at Buffalo, and Chair of the Department of Biomedical Engineering. His work focuses on integrated sensors and biomedical instrumentation.*

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