Thin Photo-Patterned Micropolarizer Array for CMOS Image Sensors

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***Abstract*—We fabricated and characterized a thin photo-patterned micropolarizer array for complementary metal–oxide–semiconductor (CMOS) image sensors. The proposed micropolarizer fabrication technology completely removes the need for complex selective etching. Instead, it uses the well-controlled process of ultraviolet photolithography to define micropolarizer orientation patterns on a spin-coated azo-dye-1 film. The patterned polymer film micropolarizer (10 μm × 10 μm) exhibits submicron thickness (0.3 μm) and has an extinction ratio of $\sim$100. Reported experimental results validate the concept of a thin, high spatial resolution, low-cost photo-patterned micropolarizer array for CMOS image sensors.**

***Index Terms*—Complementary metal–oxide–semiconductor (CMOS) image sensor, micropolarizer array, polarization imaging.**

I. INTRODUCTION

RAPID advances in semiconductor industry complementary metal–oxide–semiconductor (CMOS) fabrication process have enabled the integration of a camera onto a single silicon chip. Referred to as CMOS image sensor, a camera-on-a-chip offers significant advantages in terms of system miniaturization and manufacturing cost [1]. As a result, CMOS image sensors can now be found in a wide range of consumer electronic products from mobile phones, PC mouse, and webcam to fax machines, to name a few. Like the vast majority of commercially available camera systems, CMOS image sensors are essentially designed to image the world in terms of intensity and color. To capture the third characteristic of light that is polarization, Kalayjian *et al.* proposed to integrate a micropolarizer array on top of the image sensor [2]. A number of implementations have subsequently been proposed [3]–[5]. In each case, selective etching was required to pattern the micropolarizer at the pixel pitch [2]–[5]. In this letter, we propose a novel micropolarizer array fabrication technology that removes the need for selective etching, which is a difficult process to control at the micrometer scale [5]. Instead, we propose to use the well-controlled-process of ultraviolet (UV) photolithography to enable the patterning of a high resolution pixel-level micropolarizer array layer with submicron thickness. We describe this novel micropolarizer fabrication technology in Section II. We report and discuss experimental results in Section III. Finally, a conclusion is drawn in Section IV.

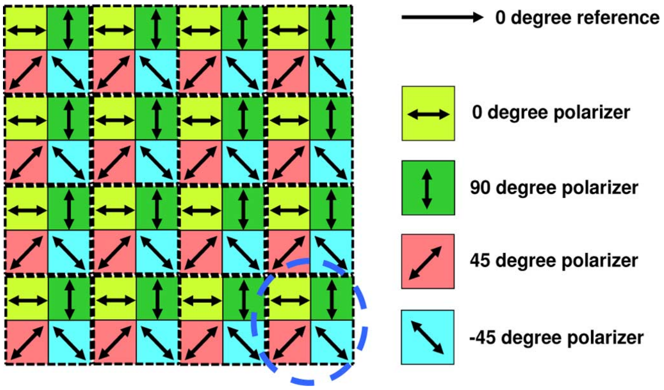

Fig. 1. Micropolarizer array pattern.

II. MICROPOLARIZER ARRAY

A. Design

All possible states of polarization can be represented in one vector known as a Stokes vector. The Stokes vector provides information about reflecting objects that traditional intensity/color-based cameras ignore. Concretely, surface features, shape, shading, roughness, specularities, occluding contours, and material properties can be readily extracted if the Stokes vector components are available. The Stokes vector describes the polarization of light through four components

$$\begin{aligned} S_0 &= I(0^\circ, 0^\circ) + I(90^\circ, 0^\circ) \\ S_1 &= I(0^\circ, 0^\circ) - I(90^\circ, 0^\circ) \\ S_2 &= I(45^\circ, 0^\circ) - I(-45^\circ, 0^\circ) \\ S_3 &= I(45^\circ, 90^\circ) - I(-45^\circ, 90^\circ) \end{aligned} \tag{1}$$

where $I(x^\circ, y^\circ)$ represents the intensity of light measured through an x degree linear polarizer, after a phase shift of y degree. The circular polarization component S_3 describes the excess of left-hand circularly polarized portion over the

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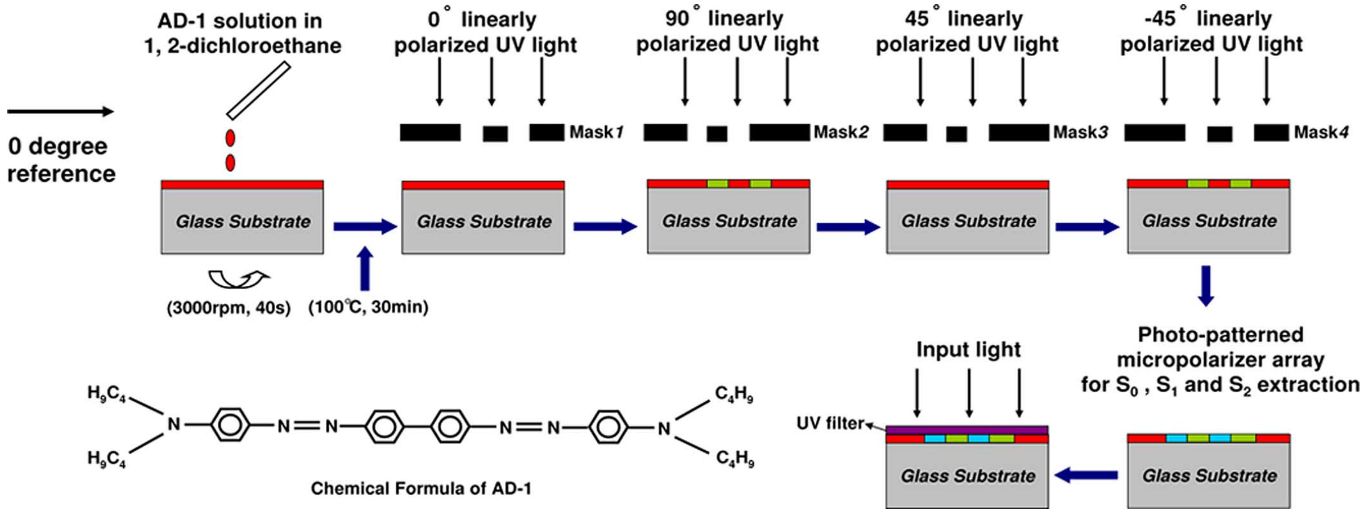
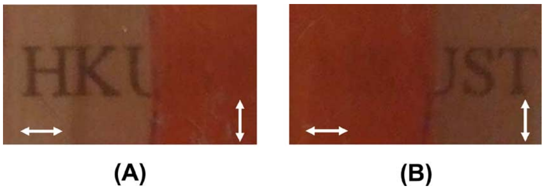


Fig. 2. Proposed photo-patterned micropolarizer array fabrication process flow.



(A) (B)

Fig. 3. Dichroism of AD-1: (A) with 0° linear polarizer on top; (B) with 90° linear polarizer on top.

right-hand circularly polarized portion, which is very rare in the intended applications.

To determine the Stokes components, we propose to adopt an approach similar to that used in a color filter array (CFA). The micropolarizer array pattern is presented in Fig. 1. Here, each pixel will look through either a micropolarizer of 0°, 90°, 45°, or −45° (Fig. 1). As a result, a single intensity value is available per pixel. The three other missing intensity values are recovered by examining the intensity values of neighboring pixels. A 2×2 (or larger) convolution kernel can be applied to estimate the first three Stokes parameters at each point. This approach trades off spatial resolution to allow for polarization measurements to be made simultaneously. In essence, this process is similar to CFA interpolation or demosaicing.

B. Fabrication

A photosensitive material azo-dye-1 (AD-1) was first synthesized for the photo-patterning of the micropolarizer array (Fig. 2). This material exhibits a strong dichroism after sufficient exposure to linearly polarized UV light (Fig. 3). The local polarization axis is formed in the illuminated regions of the AD-1 film. The degree of molecular order depends on the exposure energy. The polarizing axis of the photo-induced AD-1 linear polarizer is in parallel with the polarizing orientation of the projected UV light, which corresponds to a stable configuration [6]. With the well-controlled process of photolithography, different micropolarizer array patterns can be transferred onto a single AD-1 layer using appropriate masks and UV polarizers. The fabrication steps (Fig. 2) required to photo-pattern the micropolarizer array can be outlined as follows:

1) A solution of AD-1 in 1,2-dichloroethane is filtered and spin-coated on top of an ultraviolet-ozone precleaned glass substrate. The transparent glass substrate corresponds to the passivation layer covering the image sensor. Because the imager substrate is opaque, we did not directly fabricate the micropolarizer on top of the imager. Instead, we patterned on a transparent glass substrate, which enables us to measure the transmittance and extinction ratio of the micropolarizer and evaluate its performance.
2) Immediately after the spin coat, the sample is baked at 100 °C for 30 min in order to remove the solvent and strengthen the adhesion of the AD-1 film to the glass substrate.
3) The sample is then exposed to linear polarized UV light with 0°, 90°, 45°, and −45° orientations. Four different photolithography masks are applied successively to form the micropolarizer array pattern of Fig. 1. The exposure time is 30 min. A 1000-W Xenon arc lamp and a UV sheet polarizer from Oriel Instruments were used. The intensity of the polarized UV light at 365 nm was about 6 mW/cm^2.

III. EXPERIMENTAL RESULTS

A. Measurements

Fig. 4 presents the microphotographs of the fabricated micropolarizer array. Linear polarizers with 0°, 90°, 45°, and −45° orientations were placed on top of the sample to visualize the orientations of the pixel-level micropolarizers. The reported micropolarizer pitch of 10 μm$\times$10 μm here (Fig. 4) is not an indication of the resolution limit of the proposed implementation but only the result of the use of readily available general masks. The resolution limit (i.e., minimum micropolarizer pitch) of the proposed micropolarizer fabrication technology is set by the resolution of the adopted photolithography process. In order to evaluate the optical performance of the micropolarizer array, the two equally important figures of merit that are the

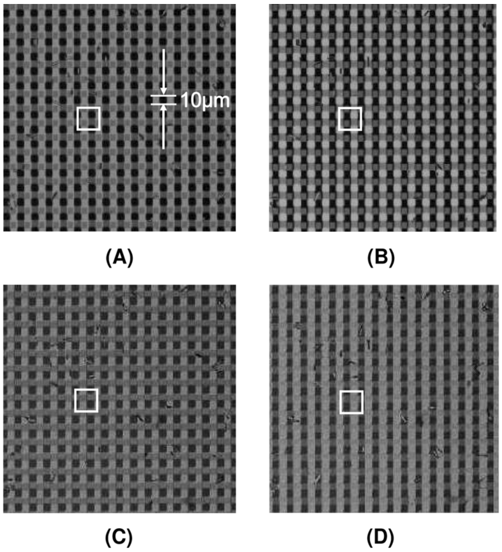


Fig. 4. Microphotographs of the fabricated micropolarizer array: (A) with 0° linear polarizer on top; (B) with 90° linear polarizer on top; (C) with 45° linear polarizer on top; (D) with −45° linear polarizer on top.

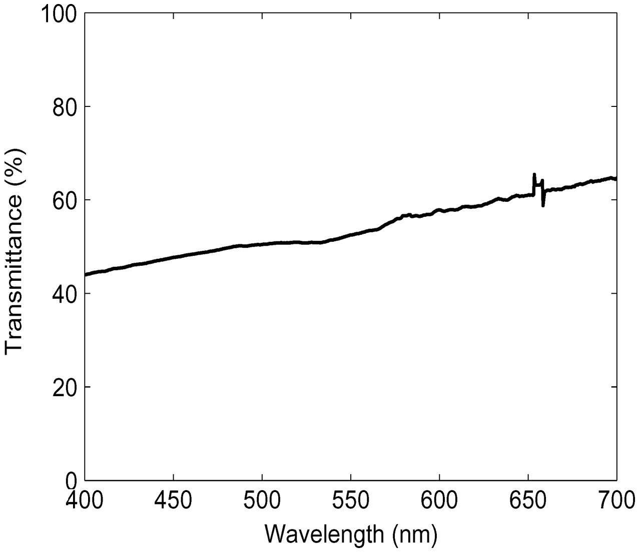


Fig. 5. Spectral measurement results of the major principal transmittance.

major principal transmittance and the extinction ratio have been extracted [7]. Fig. 5 reports the major principal transmittance measured with the wavelength varied from 400 to 700 nm. An extinction ratio of ∼100 was measured for a 4wt% solution of AD-1 in 1,2-dichloroethane.

B. Discussion

The proposed photo-patterned micropolarizer fabrication technology has the following characteristics.

1) The AD-1 film (Fig. 2) is photo-chemically stable against subsequent UV, moisture, and thermal exposure [6]. Vacuum packaging protects the sensor from lifetime environmental exposure. As for the temperature, the photo-induced dichroism of AD-1 is stable up to 130 °C.
2) An extinction ratio of ∼100 compared to a maximum value of ∼1000 for commercially available polyvinyl alcohol films. We are currently working at further increasing the value of the extinction ratio by optimizing process parameters such as spin-coating speed and sensitivity/concentration of the AD-1.
3) Reduced crosstalk between adjacent photodetectors as illustrated in Fig. 6 with oblique incident light.
4) High spatial resolution only limited by the resolution of the selected photolithography process. The latter provides far better control compared to previously reported etching-based patterning [2]–[5].
5) Simple CMOS compatible fabrication process, which only requires the standard fabrication steps of spin-coating and UV-photolithography.

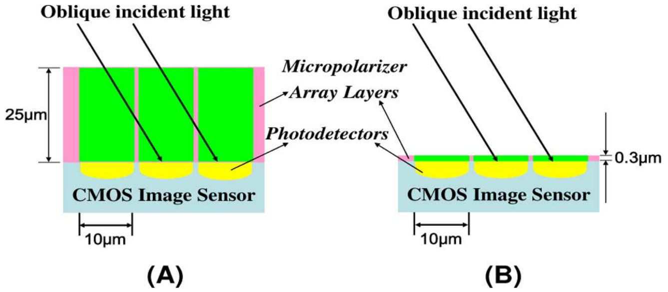


Fig. 6. Influence of the micropolarizer array thickness on signal crosstalk with oblique incident light (10-μm uniform micropolarizer pitch size is chosen here to facilitate the comparison): (A) [5] *Gruev* ; (B) this work.

IV. CONCLUSION

We have reported a photo-patterned micropolarizer array for CMOS image sensors. The proposed implementation is relatively simple, CMOS compatible, and enables the real-time extraction of the first three parameters of Stokes vector with a fully integrated polarization image sensor. Reported experimental results have demonstrated the potential of the photo-patterned method with submicron thickness and high spatial resolution. The proposed micropolarizer array can be fabricated directly on top of a CMOS image sensor array to enable polarization imaging. Ongoing efforts are underway to optimize the fabrication process and further improve the performance of the photo-patterned micropolarizer array.

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