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Microfabrication of a color filter array utilizing colored SU-8 photoresists

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Patterned color filter arrays are important components in digital cameras, camcorders, scanners, and multispectral detection and imaging instruments. In addition to the rapid and continuous progress to improve camera resolution and the efficiency of imaging sensors, research into the design of color filter arrays is important to extend the imaging capability beyond conventional applications. This paper reports the use of colored SU-8 photoresists as a material to fabricate color filter arrays. Optical properties, fabrication parameters, and pattern spatial resolution are systematically studied for five color photoresists: violet, blue, green, yellow, and red. An end-to-end fabrication process is developed to realize a five-color filter array designed for a wide angle multiband artificial compound eye camera system for pentachromatic and polarization imaging. Colored SU-8 photoresists present notable advantages, including patternability, color tunability, low-temperature compatibility, and process simplicity. The results regarding the optical properties and the fabrication process for a colored SU-8 photoresist provide significant insight into its usage as an optical material to investigate nonconventional color filter designs.

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1. INTRODUCTION

Color filter arrays (CFA) are used extensively in image sensors with broad wavelength sensitivity to record color information. The most common configuration of a CFA is the Bayer CFA, using the division of the focal plane method with three primary-color filters in red, green, and blue (RGB) that mimics the trichromatic vision of the human eye [1]. The ideal material for CFAs should have low loss in the transmitted wavelength band and high loss in the blocked wavelength band. The material must also be compatible with conventional semiconductor processes, and allow high-resolution patterning. Organic photosensitive polymer filters are the most commonly used in consumer cameras. Photosensitive resists, either in a positive or negative tone, doped with color dyes or pigments are used to fabricate CFAs using photolithography techniques [2–4]. Patterning pre-dyed positive photoresists requires a long period of stabilization, baking at relatively high temperatures, which causes a yellowing of the photoresists and changes the optical clarity of the patterns [3]. A pre-dyed negative photoresist system, which uses free-radical-initiated photopolymerization as a mechanism for patterning, can resolve features less than 2 μm in size using lower doses [4]. However, the patterns display rounding and sloping side walls due to oxygen radical quenching at the resist surface. A different approach to obtain color patterns is the dye transfer technique [5]. Color dyes in red, green, and blue were transferred from color-containing sheets to a dye-accepting polymer at a high temperature, but inconsistencies in color intensity and uniformity have limited this approach from being widely adopted. Multilayer inorganic materials with different refractive indices have also been used as color filters [6,7], and the deposition and patterning, either by etching or liftoff processing, added complexity to the fabrication. Other CFAs such as metal–insulator–metal (MIM) Fabry–Perot cavities have also been explored [8]. To demonstrate the concept at the wafer level, 30 μm × 30 μm pixels are realized in a SU-8 photoresist sandwiched between two metal layers. The various thicknesses of the SU-8 patterns, for nine color bands, were obtained using grayscale lithography through nine exposure steps with different dosages. The results demonstrate good transmission efficiencies with narrow bands and no polarization dependency. A recent development in nanotechnology enables design and fabrication of photonic crystals and plasmon-assisted structural color filters. These filters use geometrical resonances to manipulate light in visible frequencies and further engineer surface waves at the nanoscale [9,10]. Moreover, transmissive color filters based on subwavelength dielectric gratings can be

used as RGB color filters with a peak transmittance of 60–80% [11]. Finally, dielectric pixel-scale color splitters were used in an image sensor, providing light detection enhancements of up to 3.57 with a spatial resolution of 0.43 μm [12]. Indeed, the visual quantity of a full-color image depends, to a great extent, on the CFA design, fabrication, and demosaicing processes during imaging formation and color reconstruction [13]. It remains, therefore, a constant goal to design low-loss CFAs with high resolution but without a significant increase in complexity in the fabrication and implementation [14,15].

In parallel with the continuous activities to further improve the resolution and efficiency for conventional cameras, research efforts investigating new color filter designs for novel applications are vigorously pursued. For example, color filters with a visible spectrum of 300–750 nm are of a great interest. This visible spectrum range represents those of some insects and animals in nature, such as birds, reptiles, and butterflies [16], extending on both ends of the human visible spectrum of RGB. To realize proof-of-concept designs of novel color filters, new material and fabrication process are needed, which can realize CFA design functionality with a quick turnaround for cost-effective research and development as well as rapid prototyping. Negative photoresist, SU-8, has played an unmatchable role in the development of microfabrication technology. Its stable chemical and mechanical properties offer a wide range of applications in the development of microscale structures, functional components, integrated microsystems, and microfluidic systems and lab-on-a-chip devices in particular [17–19]. SU-8 resists also possess excellent optical properties [20], demonstrating their important role in the development of optical components and systems, including waveguides [21–26], lenses [27,28], integrated photonics [29], optofluidic systems, and microstructures for biosensing [30–33]. Abundant methods and techniques have been reported about fabrication processes using colorless SU-8 photoresists [34–41].

Pre-dyed SU-8 photoresists are commercially available (Gersteltec Sarl, Pully, Switzerland). In this work, we examine optical spectra of five colored SU-8 photoresists in violet, blue, green, yellow, and red as CFA materials. We further systemically investigate fabrication parameters to realize patterns using photolithography techniques. We establish contract curves for exposure of the five colored SU-8 photoresists, and evaluate pattern resolutions and fidelity. For the first time, to the best of our knowledge, we demonstrate the design and fabrication of a color filter array with five color bands using colored SU-8 photoresists.

2. METHODS

A. Materials

Colored SU-8 photoresists are commercial products from Gersteltec Sarl, Switzerland. A colored SU-8 resist is a homogeneous mixture of metal complex dyes incorporated, as a guest, into a polymer matrix of a colorless SU-8 photoresist, which serves as the host. The host SU-8 photoresist (GM1040, Gersteltec Sarl, Pully, Switzerland) contains 38%wt of EPON SU8 resin, 2% of a photo-acid generator (PAG), and 60%wt of a gamma butyrolactone solvent. The PAG is a 50/50 mixture of propylene carbonate and triarylsulfonium hexafluoroantimonate salt with a maximum absorption at 320 nm. The viscosity of the photoresist is 60 ± 2 mPa · s at 20°C measured at a shear rate of 200 s^{-1}. The dyes are miscible in the host photoresist and stable up to 140°C. The colored SU-8 photoresists are prefiltered, and have a nominal shelf life of six months. For this study, we acquired five colored SU-8 photoresists, in violet, blue, green, yellow, and red, with optical specifications serving our design of a five-color filter array. The colorless SU-8 photoresist, as the host of all the five color photoresists, allows the acquisition of a photoresist film with a thickness ranging 0.9–4.6 μm under a spin-coating speed in the range of 1000–5000 rpm. Other lithography materials, such as SU-8 developer, positive photoresist Shipley Microposit S1813 and developer MF-319, were purchased from MicroChem Corp., Westborough, MA, USA. Double-side polished Corning Gorilla glass wafers, 38 mm or 100 mm in diameter, were purchased from Valley Design Corp., Santa Cruz, CA, USA. The 0.55 mm thick glass wafers have excellent optical transmittance over the entire wavelength range of interest (400–750 nm), and are used as the substrates. Glass substrates were prepared following a standard procedure. Briefly, a glass wafer was first cleaned using semiconductor-grade acetone and isopropyl alcohol (IPA), and blow-dried with nitrogen. The coating surface was then treated under O_2 plasma for one minute before promptly dispensing and spin-coating a photoresist on the wafer.

B. Experiment to Establish Contrast Curves for Exposure

To establish contrast curves for exposure for the colored SU-8 photoresists, a set of samples of crosslinked films on glass substrates were obtained for each colored SU-8 photoresist. In this experiment, the film thickness of a sample corresponds to only the ultraviolet (UV) exposure dosage, assuming a constant development rate. The sample preparation started with dispensing an appropriate amount of a color photoresist on a glass substrate using a syringe. A film with a designated thickness was obtained on the glass substrate by spin-coating using a Laurell spin-coater at a selected speed. After soft-baking on a hotplate at 65°C for 5 min and 95°C for 5 min, the sample was placed on the stage of a Karl Suss MA6 aligner with the film facing down. The film was flood-exposed, through the glass substrate, by a UV light source (Hg lamp) with a power density of 13.3 mw/cm^2 at 365 nm operated for broadband exposures (350–450 nm). The sample was subsequently post-baked at 65°C for 60 min, and then developed in a bath of SU-8 developer at room temperature until a residual-free film was realized on the glass substrate. Finally, the sample was rinsed with IPA and blow-dried with nitrogen. Specifically, films with an initial coating thickness of 3.5 μm were prepared for the violet, blue, yellow, and red photoresists. For the green photoresist, in particular, films with an initial coating thickness of 2.5 μm were prepared so that the dosages needed to obtain crosslinked films in a green photoresist are practical for our application. Furthermore, a scheme for exposure was used to avoid UV irradiation-associated heating in the photoresist films during long-duration UV exposures, where a full dosage was completed by multiple cycles of a 3-min short exposure with a 1-min interval between consecutive exposures. For each color photoresist, samples were prepared with various thicknesses corresponding to a series of about 20 dosages. A Bruker Dektak

surface profilometer was used to measure the film thicknesses of all the samples.

C. Experiment to Examine Pattern Resolution

The colored SU-8 photoresists, as negative photoresists, can be patterned by selective UV exposures. To examine the pattern resolution, a blue color photoresist, as an example, was patterned using an Air Force 1951 USAF target photomask. The dark-field photomask consists of groups and elements of equal-width line patterns, which are spaced apart by gaps with the same width in a range of 1 μm–1 mm [42]. The blue-colored SU-8 photoresist was dispensed on a 100-mm diameter glass wafer. A 3-μm-thick film was obtained on the wafer using spin coating at 2000 rpm for 60 s. After prebaking at 65°C for 5 min and 95°C for 5 min, the film was exposed by the same UV light source of the Karl Suss MA6 aligner through the photomask in soft-contact mode. The UV exposure, of a total dosage of 48 J/cm^2, was completed by 20 cycles of a programed exposure (i.e., 3 min exposure and 1 min rest). The film, after post-baking at 65°C for 60 min, was developed in a bath of SU-8 developer at room temperature for about 2 min till residual-free photoresist patterns were obtained on the glass substrate. The sample was finally rinsed with IPA and blow-dried with nitrogen, and hard-baked at 95°C for 5 min. Microscopic imaging was performed to examine the pattern dimensions and quality. A Bruker Dektak surface profilometer with a 12.5 μm radius tip was used to obtain the pattern profiles.

D. Experiment to Characterize Colored SU-8 Resist Optical Spectra

Optical spectra of the colored SU-8 photoresists were characterized. Samples of SU-8 color resist films were prepared on the glass substrates using the following steps. An appropriate amount of a colored SU-8 photoresist was dispensed onto a glass substrate using a syringe. A film was obtained on the substrate by spin coating using a Laurell spin coater. After prebaking on a hot plate at 65°C for 5 min and 95°C for 5 min, the film was exposed by the same UV light source using the Karl Suss MA6 mask aligner. Appropriate exposure dosages were used for films of different color photoresists with different thicknesses to obtain fully crosslinked films. Post-exposure baking was performed at 65°C for 30 min. Films that were only prebaked (i.e. without UV exposure or post-baking), serve as uncrosslinked samples, whereas those that underwent all the steps of prebaking, UV exposure, and post-baking were used as crosslinked samples.

For the characterization, samples of crosslinked blue SU-8 resist films with five thicknesses in a range of 1.6–4.5 μm were obtained. Samples of 3 μm thick films, uncrosslinked and crosslinked, of violet, yellow, blue, and red resists were obtained. For the green photoresist, in particular, 2 μm thick crosslinked films were obtained. A samples of crosslinked 3 μm thick colorless SU-8 resist film was also obtained for comparisons. Film thicknesses were measured using a Bruker Dektak surface profilometer, and their optical spectra were collected using a Cary 5000 spectrophotometer in the wavelength of 350–800 nm.

3. RESULTS

A. Contrast Curves for Exposure of the Colored SU-8 Photoresists

The photoresist contrast curve, or the Hurter–Driffield (H–D) curve, is generally used to describe the correlation between the irradiation dosage and the crosslinked photoresist film thickness, assuming a constant development rate throughout the photoresist film [43–46]. A typical characteristic curve for a negative photoresist is illustrated in Fig. 1(a), establishing the relationship between the normalized thickness, H, of a crosslinked film and the logarithm of exposure dosage, $\log_{10} D$. The curve shows that the film thickness, H, increases linearly with increasing $\log_{10} D$ for a majority of the dosage range (i.e., the linear region). Here, D_0 is the lowest dose, often denoted as the gel dose, to obtain the thinnest possible photoresist film. D_1 is the saturation dose, above which a photoresist film is fully crosslinked through its thickness. Conventionally, the contrast of a photoresist, γ, is defined by the maximum slope of the contrast curve (i.e., the slope of the linear region) as

$$\gamma = \left[\frac{dH(D)}{d(\log_{10} D)}\right]_{\max} = \frac{1}{\log 10\left(\frac{D_1}{D_0}\right)}. \quad (1)$$

The sensitivity of a photoresist is defined as the dosage $D_{\frac{1}{2}}$ to obtain half of the film thickness, $H_{\frac{1}{2}}$. In general, a high-performance photoresist has a low $D_{\frac{1}{2}}$ and a high γ.

The dependences of the crosslinked film thickness on the dosage, for all five SU-8 colored photoresists, were experimentally obtained and are summarized in Fig. 1(b). The measured data show that the relationship between the film thickness, H, and the dosage, D, for each colored resist, indeed displays a similar trend, as shown in Fig. 1(a). The relationship can be described using [41–44]

$$H(D) = 1 - a \cdot 10^{-\frac{D}{b}}, \quad (2)$$

where $H(D_0) \to 0$, and $H(D_1) \to 1$. Parameters a and b are fitting constants, where a is unitless and b is in unit of dosage. Fitting curves for the five color resists are plotted against the measured data, and the values of the contrast and sensitivity for the five color photoresists are summarized in the table in Fig. 1(b).

From the measured data for the five color photoresists in Fig. 1(b), the violet color photoresist has the highest sensitivity of 1.5 J/cm^2, but the lowest contrast of 0.56. The yellow color photoresist displays the highest contrast of 1.43, with a sensitivity of 4.4 J/cm^2. The blue photoresist has a good contrast of 0.94, with a sensitivity of 4.8 J/cm^2. The red and green photoresists show good contrasts of 0.98 and 1.05, respectively; however, both have very low sensitivities of 25.3 J/cm^2 and 39.5 J/cm^2, respectively. The sensitivity of a photoresist corresponds to the effective energy that the PAG receives from the UV exposure energy. Colored dyes in the photoresists absorb a portion of the UV energy. The amount of the absorption for the five colored SU-8 photoresists varies, resulting in the differences in the sensitivity. The optical properties of the five colored SU-8 photoresists are systemically investigated and the results are presented in this section. It is important to note that the

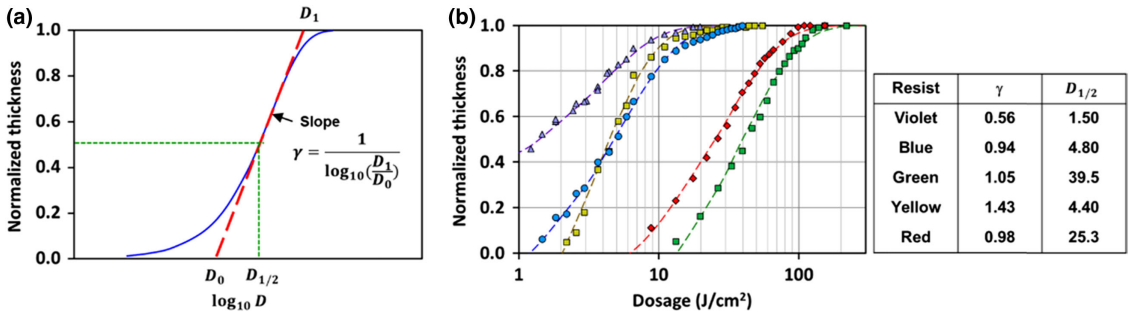


Fig. 1. (a) Schematic of a characteristic curve for a negative photoresist shows the gel dosage D_0 and the saturation dosage D_1, as well as the sensitivity $D_{1/2}$ (J/cm^2), and the contrast γ. (b) Experimental data (symbols) are compared to characteristic curves for the five color photoresists. The dashed curves are fitting curves based on Eq. (2). The colors assigned to the symbols and the fitting curves correspond to the colors of the photoresists. The contrasts and sensitivities of the five color photoresists are summarized in the table inset.

exposure dosages shown in the contrast curves were obtained by flood exposures of the resist films through a 0.55 mm thick glass substrate in the absence of a chrome photo-pattern mask. The actual dosages to obtain patterns in the color photoresist films of particular thicknesses must be specifically obtained, taking into account effects such as the glass absorptions and interfaces, as well as the pattern feature size.

B. Pattern Resolution

Patterns of blue SU-8 photoresist were obtained on a 100 mm diameter glass wafer. Excellent color uniformity is seen in the line patterns over the entire wafer, as shown in Fig. 2(a). Good quality patterns with well-defined edges and accurate dimensions are demonstrated for a line-width down to 100 μm (Group 2, element 3), as shown in the microscope image in Fig. 2(b). Lines with a width larger than 50 μm are well defined. With a further reduction in the line width to 35 μm (Group 3, elements 6) as shown in Fig. 2(c), however, the line patterns appear slightly wider while the gaps between adjacent lines are narrower than the designed width. This phenomenon is more pronounced for line widths of less than 30 μm, where the width of the lines is much larger than that of the gaps and residuals of resist are present around the pattern edges.

Pattern resolution and quality are further evaluated by examination of the pattern profiles obtained using a Bruker Dektak surface profilometer with a 12.5 μm radius tip. As shown in Fig. 3(a), the measured profiles show vertical side walls with a uniform thickness of 3.10 μm for line/gap widths larger than 100 μm (Group 2, elements 2 and 3). With a reduction in the

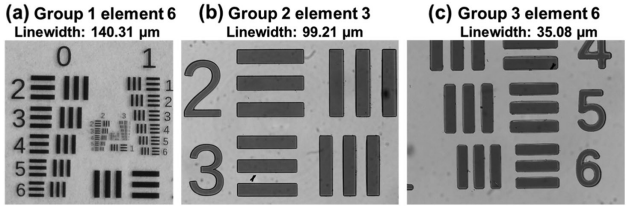


Fig. 2. Images of blue photoresist patterns are shown with information on linewidths. (a) Patterns are realized on a 100 mm diameter glass wafer with uniform color. (b) Microscopy image of the patterns in Group 2 (elements 2 and 3) is shown. (c) Microscopy image of patterns in Group 3 (elements 4, 5, and 6) are shown.

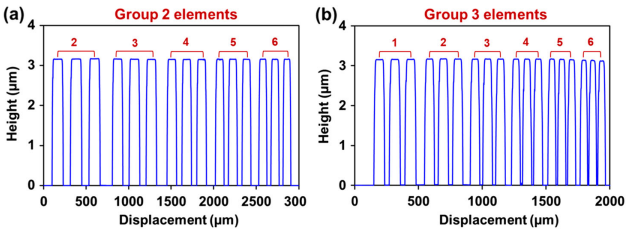


Fig. 3. Pattern profiles obtained by a Bruker Dektak surface profilometer show the linewidth of (a) elements 2–6 in Group 2 with nominal linewidths of 111.36–70.15 μm, and (b) elements 1–6 in Group 3 with nominal linewidths of 62.50–35.08 μm.

line/gap width to 70 μm (Group 2, elements 4, 5, and 6), the sidewalls of the patterns are not perfectly vertical, displaying slightly overcut profiles. Similarly, for lines with a width from 62.50 μm down to 39.37 μm (Group 3, elements 1–5), as shown in Fig. 3(b), the line patterns appear not to have vertical sidewalls. The patterns look wider at their bases on the glass substrate than at the top surface of the photoresist layer. For a smaller line/gap width of 35.08 μm (Group 3, element 6), the gap between adjacent lines at the substrate cannot be resolved properly by the profilometer. Examination of the images of the patterns indicates that the lines are about 40 μm wide, whereas the gaps between two adjacent lines are about 30 μm wide. The stylus tip of the profiler terminates in a 45° cone with an end radius of 12.5 μm. For wider gaps of more than 30 μm, the profiler tip is able to make direct contact with the bottom surface at the gap, thus providing correct profiles for the patterns. For narrow gaps of less than 30 μm in width, however, the tip is limited to properly reach the bottom surface of a gap, and is thus unable to obtain accurate pattern profiles. The study on pattern resolution demonstrate that patterns/gaps larger than 50 μm can be realized with satisfactory quality in 3 μm thick films of colored SU-8 photoresists. Similar to UV lithography with colorless SU-8 photoresists and other types of photo-patternable material, patterning colored SU-8 photoresists for a particular dimension requires a set of processing parameters that are optimized for that dimension. Patterns with smaller dimensions, on the order of a micrometer, can be obtained in thinner films and/or by acquiring and using specifically optimized processing parameters.

C. Optical Spectra Characterization of Colored SU-8 Photoresists

Transmittance spectra of the colored SU-8 photoresists are key to their application as optical color filters. Optical spectra of the five colored SU-8 photoresists are investigated to evaluate the optical performances. The measured transmission spectrum of a 3 μm thick colorless SU-8 resist film on glass substrate, together with the spectra of a set of crosslinked blue resist films of five thicknesses ranging from 1.4 μm to 4.6 μm, are shown in Fig. 4(a). The colorless SU-8 film displays a constant transmittance of 90% in the wavelength range of 350–800 nm, as expected. The spectrum of each blue resist film exhibits a similar profile, with a peak at 450 nm and valleys elsewhere in the wavelength range of 350–800 nm. Varying film thickness does not change the profile shape and peak/valley wavelengths. The spectral profile drops in its transmittance level for all wavelengths with increasing film thickness. As presented in Fig. 4(a), the peak and valley transmittance values reach about 90.0% and 33.8%, respectively, for the 1.6 μm thick film, whereas they are 89.0% and 2.1%, respectively, for the 4.5 μm thick film. The results suggest that a desired combination of peak/valley transmittance values can be obtained by adjusting the film thickness of a colored SU-8 photoresist.

We further investigate whether the fabrication process results in any discrepancies in the optical performance of colored SU-8 photoresists. Spectral data are obtained from samples with 3 μm thick photoresists in violet, yellow, blue, and red, and a 2 μm thick photoresist in green. Figures 4(b)–4(f) compare transmission spectral profiles from samples of uncrosslinked films (dashed lines) and crosslinked films (solid lines), for each color photoresist, respectively. The spectral profiles of the five color dyes (dotted lines) are also included, where the wavelengths at the peak and valley are compared to those of the dye-photoresist mixtures, respectively. For the violet photoresist, as shown in Fig. 4(b), the spectral profile shape for all three cases are similar, with the peak transmission at 430 nm. For the blue photoresist, as shown in Fig. 4(c), the spectra for the uncrosslinked film and crosslinked film are identical, with the peak transmission wavelengths at 450 nm. The peak wavelength for the films shifts about 20 nm compared to that of the color dyes at 470 nm. For the green photoresist, the spectral profiles are identical for all the three cases, with the peak transmission wavelength at 550 nm. However, the spectral profile elevates to a higher transmittance level after UV crosslinking, as shown in Fig. 4(d). For the yellow photoresist, the spectral profiles of the films, uncrosslinked and crosslinked, are identical, as shown in Fig. 4(e), displaying as a long-pass filter. The shoulder of the peak transmission is at 600 nm, shifting about 10 nm from that of the color dyes at 610 nm. For the red photoresist, the spectra show similar long-pass filter profiles as that of the yellow resist. They are identical for the color dyes and the uncrosslinked film, with the shoulder of the peak transmission at 620 nm. The spectral profile for the crosslinked film, however, changes to a lower transmittance level in the peak wavelengths but changes to a higher transmittance level at the valleys, as compared in Fig. 4(f). The shoulder of the peak transmission of the crosslinked film is also shifted about 20 nm to be at 640 nm. In summary, the transmission profiles confirm that the crosslinked films of the five color photoresists provide the design optical performance in the five specific spectral bands. Furthermore, the spectra show minimal discrepancies in the spectral profiles between the design specifications and the measured data of crosslinked films, which experienced all steps of the fabrication process. The slightly elevated or dropped transmittance levels can be resolved by adjustment of the film thicknesses, whereas the small shifts in peak wavelength, within 20 nm, can be precalibrated in photoresist formulations by fine-tuning the dye spectral specifications.

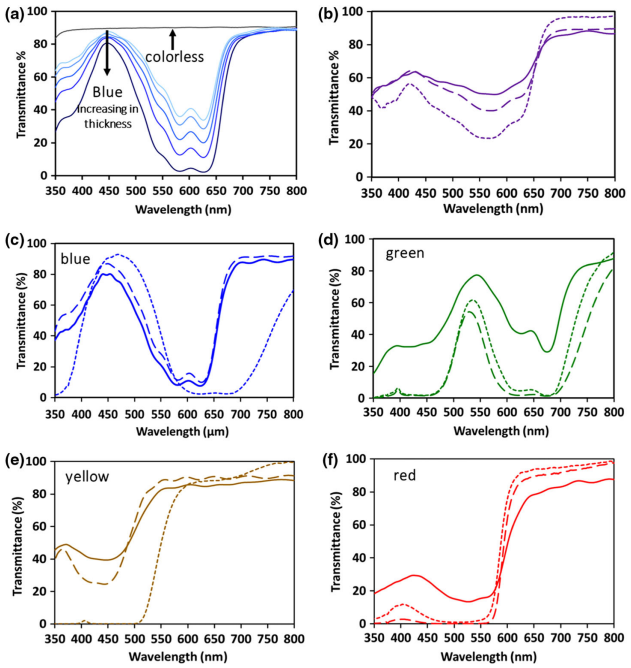


Fig. 4. (a) Transmission spectra of crosslinked films of 3 μm thick colorless-SU-8 and blue SU-8 with various thicknesses 1.6–4.5 μm are shown. (b)–(f) Comparison of transmission spectra of color dyes (dotted lines), uncrosslinked films (dashed lines), and crosslinked films (solid lines) for (b) violet, (c) blue, (d) green, (e) yellow, and (e) red color resists are shown. The film thicknesses are 3 μm for the violet, yellow, blue, and red photoresists, and 2 μm for the green photoresist.

The peak wavelengths for the three photoresists are identified from the spectra shown in Figs. 4(b)–4(f) (i.e., 430 nm for violet, 450 nm for blue, and 550 nm for green, respectively). The yellow photoresist and the red photoresist exhibit long-pass transmittance filter profiles. Accordingly, transmittance values at 610 nm and 700 nm are used, respectively, to represent the high transmission values of the yellow photoresist and the red photoresist. Figure 5(a) summarizes the peak transmission values measured from the crosslinked films of the five color resists, where the value from a 3 μm thick crosslinked film of colorless SU-8 photoresist is provided as a reference. The values of the peak transmittance of blue, green, yellow, and red color resist films are close to 80%, whereas the value for the violet photoresist is about 60%. These values of peak transmittance meet the color filter array design specifications. The absorbance values of the colored SU-8 photoresist films at the UV wavelength are important parameters since UV exposure is used to crosslink the colored SU-8 photoresists. Figure 5(b) summarizes the measured absorbance values of unexposed films and exposed films of the five color resists at 365 nm. The absorbance values of

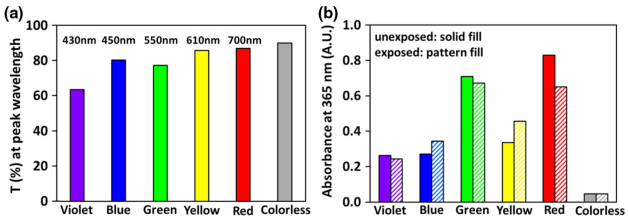


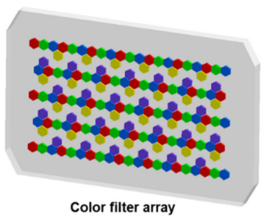
Fig. 5. Measured data on (a) peak transmittance and (b) absorbance values at 365 nm for films of the five color photoresists and the colorless SU-8 are displayed in bar chart format.

the unexposed and exposed colorless SU-8 films are provided for comparison. The absorbance values for the colored SU-8 resists are in the range of 0.3–0.8, which are indeed increased by one order of magnitude compared to the values of 0.05 for colorless SU-8 photoresists. Small discrepancies are observed between the absorbance values of the unexposed and exposed films, which are shown in Figs. 4(b)–4(f) due to the spectral profile shift. The remarkable increases in absorbance values at 365 nm in colored SU-8 photoresist films signify that much higher dosages of UV irradiation are necessary to activate the PAG in the colored SU-8 photoresist films.

D. Fabrication of a Color Filter Array

To establish the capability of colored SU-8 photoresists for application as an optical filter, we design and fabricate a color filter array operating in five spectral bands in the range of 350 to 750 nm. The filter array is designed for a wide angle multiband artificial compound eye camera system for pentachromatic and polarization imaging [16]. As illustrated in Fig. 6, the filter is constructed with an array of unit cells; each unit cell consists of five individual hexagonal elements in five colors arranged in a designated order in their relative positions. The hexagonal cells, having a nominal side of 1068 μm, are packed next to each other with a gap of 150 μm between any two adjacent elements. Our characterization on pattern resolution have demonstrated that good quality patterns of these dimensions are realized in colored SU-8 photoresist films. According to the design, the five colored SU-8 photoresists are used to fabricate a color filter array, which provides five spectral bands [i.e., violet (350–450 nm), blue (450–495 nm), green (495–570 nm), yellow (590–620 nm), and red (620–750 nm)].

The fabrication involved six photolithography masks for the alignment and patterning of the five colored SU-8 photoresists. Five test squares, each 1 cm by 1 cm in size, are designed on the



Color	Wavelength range (nm)
Violet	<450
Blue	450-495
Green	495-570
Yellow	590-620
Red	620-750

Fig. 6. Illustration shows the design of the color filter array constructed with unit cells consisting of five hexagonal elements in five colors: violet, blue, green, yellow, and red. The wavelength ranges for the five colors are listed in the table.

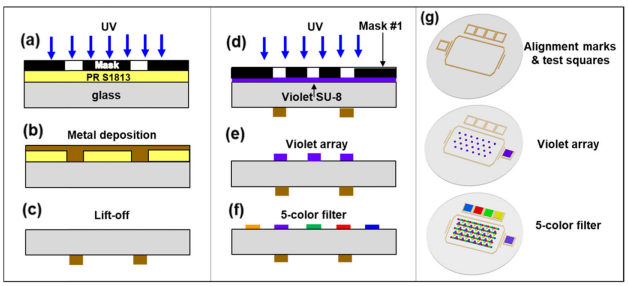


Fig. 7. Schematic of the fabrication process is shown for the five-color filter array.

same substrate for optical characterization of the five color patterns. Their locations and pattern dimensions also are defined by metal marks. Figures 7(a)–7(f) show cross-sectional views of the major steps of the fabrication process. The first step is the formation of alignment marks on the backside of a glass wafer using a lift-off process. A 1.5 μm thick positive photoresist S1813 was coated on a 100 mm diameter glass wafer. After soft-baking at 115°C for 60 s, the photoresist was selectively UV exposed at a dosage of about 320 mJ/cm^2 using the Karl Suss MA6 aligner with the soft-contact mode, as shown in Fig. 7(a). After development in MF319 developer for 45 s, the wafer was rinsed in deionized water and blow-dried with nitrogen. A layer of 100 nm thick chrome was evaporated on the substrate, as illustrated in Fig. 7(b), using an Edwards electron beam evaporator. Subsequently, a lift-off process was performed by submerging the wafer in a bath of acetone at room temperature until the chrome alignment marks were realized on the backside of the glass wafer, as shown in Fig. 7(c).

The patterns of color photoresists were fabricated on the front side of the glass wafer using similar steps described previously to pattern each color photoresist, as shown in Figs. 7(d) and 7(e). The steps were repeated for all five color resists using the sequence and parameters provided in Table 1. At completion, as shown in Fig. 7(f), patterns in five colors were realized on the glass substrate. Figure 7(g) illustrates the patterns obtained on the wafer at three stages. Each test square was fabricated *in situ* through the same process to realize patterns in one color photoresist layer. Consequently, all five test squares, together with the five color arrays, were obtained on the same wafer. A final hard-bake at 135°C for 30 min was performed to finalize the fabrication process.

Close inspection of the patterns under a microscope shows that the patterns are defect-free with accurate and well-defined corners/edges, as demonstrated in Fig. 8(a). Finally, an octagon-shaped color filter device is obtained after dicing the wafer using a die saw, as shown in Fig. 8(b). The colors in the pattern arrays are indeed uniform across the entire device. The transmission spectra for the five-color filter array, as summarized in Fig. 8(c), are obtained from the on-chip test squares, as displayed in the inset in Fig. 8(c). The results demonstrate that the color filter array accomplished its design of five spectral bands, in violet, blue, green, yellow, and red colors, with good performance.

Table 1. Fabrication Parameters for a Five-Color Filter Array Using Colored SU-8 Photoresists

Layer	Resist color	Film thickness (μm)	Pre-bake (min)		Exposure		PEB (min)		Hard bake (min)	
			at 65°C	at 95°C	Dosage J/cm^2	Cycles of 3 min exposure	at 65°C	at 95°C	at 95°C	at 135°C
1	Yellow	3	5	5	24	10	5	30	5	0
2	Violet	3	5	5	24	10	0	0	5	0
3	Blue	3	5	5	48	20	60	0	5	0
4	Red	3	5	5	96	40	60	0	5	0
5	Green	2	5	5	144	60	60	0	0	30
Ref.	Colorless	3	2	0	0.15	1	2	0	0	30

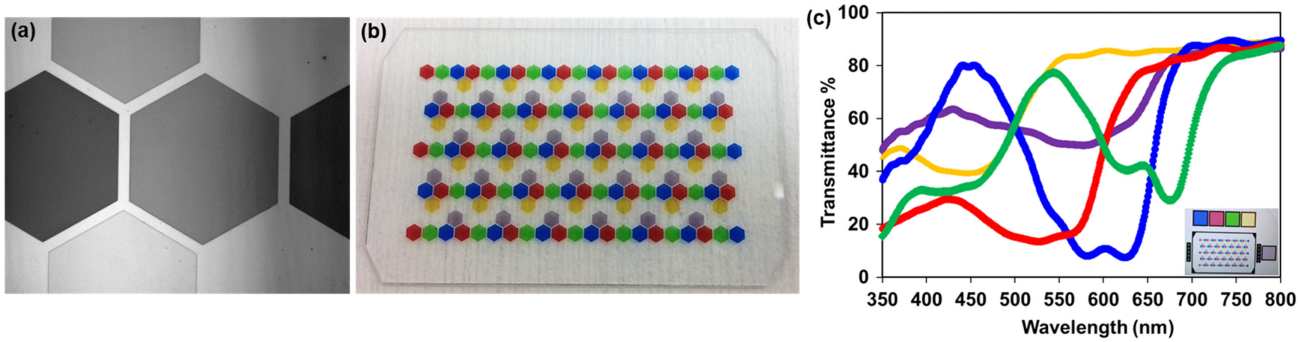


Fig. 8. (a) Microscopic image shows patterns of a unit cell consisting of five hexagonal elements in five colors. (b) Picture of a diced five-color filter device. (c) Measured transmission spectra of the color filters. The curves in violet, blue, green, yellow, and red represent the five color spectra, respectively, which are obtained from the five on-chip test squares as displayed in the inset.

4. DISCUSSIONS

Colored SU-8 photoresists are formulated according to specific customized designs by adjustments of dye selection and dye concentration in the host SU-8 photoresists. The formulation of color dyes provides a high transmittance on a specific wavelength range, but high absorption on the other wavelengths. The five color spectral bands should have little overlap to achieve good spectral performance. Unlike the sharp transitions of a multilayer interference filter [6,7], the transmission spectra of the colored SU-8 photoresists are inherently broad, which is attributed to the inhomogeneous linewidth of the dye molecules in SU-8 photoresists [47,48].

For the fabrication of color filter array, five color photoresists are processed sequentially to obtain the hexagonal elements in five colors of a color filter array. Consequently, the crosslinked photoresist patterns in the first color resist layer experience repeated baking and developing processes necessary to pattern the other color photoresist layers. We integrate the processes of the five individual color photoresists and formulate a sequence for the color filter array fabrication. At the completion of the entire fabrication process, a five-color filter array with patterns in all five colored SU-8 photoresists is successfully realized. The colored SU-8 photoresists deliver the designed optical spectra with performance and resolution comparable to existing color dye photoresists [3,4] with superior color uniformity [5], and to CFAs realized using other approaches [8]. The spectra in the patterns are true to the design specifications, and the patterns demonstrate good mechanical, chemical, and thermal stabilities, in addition to optical functionality. The pattern profiles exhibit vertical sidewalls through the thickness of the films for the design dimensions.

Similar to patterning transparent SU-8 photoresists, many factors in the UV patterning process of the colored SU-8 photoresists can affect the pattern quality. These factors include optical diffraction from the photomask, reflection, refraction at the interface between the air gap and the photoresist film in soft-contact mode, and the UV-transmitting glass substrate. Additional factors arise, in particular, in the patterning of colored SU-8 photoresists. The biggest complication in the UV patterning process of colored SU-8 photoresists is the need for high UV dosages to crosslink the negative photoresists [3]. This issue is attributed primarily to the strong UV absorption by the dyes. As a result, only a small fraction of the UV energy could be made available to active the photo-acid generator (PAG) to initiate the crosslinking process. Dosages of 10–100 J/cm^2 are needed, using the standard UV lithography, to fully crosslink a 3 μm thick colored SU-8 photoresist film, leading to reduced process efficiency and pattern resolution [4]. Other fabrication approaches, such as inkjet printing, screen printing, or imprint lithography technologies, could be explored to pattern colored SU-8 photoresists.

As observed in the patterning of the violet photoresist, hexagonal patterns appear poorly defined with round edges and corners following conventional processing steps. We attribute this phenomenon to molecular scattering (i.e., Rayleigh scattering), which can take effect in the colored SU-8 photoresist films due to optical inhomogeneities from various fluctuations [49,50]. The effect of the scattered light can be considerable due to the very high UV irradiation dosage since its intensity is

proportional to the UV irradiation intensity. We speculate that the scattered light in the exposed area of the photoresist film transmits laterally, in a short distance, into adjacent areas where direct UV is blocked by the chrome in the mask. With an appropriate dose, the scattered light exposes the photoresist beyond the pattern edges, resulting in local activation of the PAG, and consequently, noticeable poorly defined patterns after post-exposure baking. This phenomenon is uniquely observed in the patterning of the violet-colored photoresist because it has the lowest absorption of light in the UV wavelength range, allowing lateral transmission to proceed into a certain distance. The lateral transmission of the scattered light in the films of other colored photoresists, however, is lower due to their relative high absorption of light in the UV wavelength range. We accordingly have developed what we believe is a unique process to pattern the violet photoresist, where the photoresist is developed following the UV exposure, omitting the post-exposure baking. The direct UV exposure with a sufficient dosage leads to simultaneous PAG activation and UV irradiation-associated heating in the film defined by an open area in the chrome mask, which collectively and effectively result in a fully crosslinked photoresist of a pattern. In the areas of the film blocked from the direct UV irradiation, however, the effect due the UV irradiation-associated heating is minor. Consequently, crosslinking of the photoresist exposed by scattered light cannot proceed in the absence of post-exposure baking. Using this process, we are able to create fully crosslinked violet photoresist patterns with well-defined edges and corners.

To further control the effect of UV irradiation-associated heating, we divide a single, long exposure into a series of short 3 min exposures with a 1 min rest period between two consecutive exposures. In addition, we found that post-exposure baking at a lower temperature, 65°C, for an extended period of time greatly improves the pattern quality [36]. For all the baking and cooling processes, the rate of temperature change is limited to 2°C/min to minimize the introduction of stresses in the films. Since some dyes degrade and lose their optical properties above 140°C, high-temperature processes are avoided in the fabrication process.

5. CONCLUSIONS

This paper demonstrates the utility of a colored SU-8 photoresist as an optical filter material in color imaging applications. The peak transmission wavelength and magnitude of a colored SU-8 photoresist can be tuned by the formulation of color dyes in a colorless SU-8 photoresist. Colored SU-8 photoresists offer tremendous flexibility in the design of thin film patterned color optical filters because of an abundant selection of dyes, dye combinations, and dye concentrations in colorless SU-8 photoresists of various viscosities. Contrast curves for exposure of the five color photoresists, in violet, blue, green, yellow, and red, are established. The color photoresists show reasonable contrasts close to 1.0; however, generally low sensitivities, on the order of $1 - 10\ \mathrm{J/cm^2}$, are observed for crosslinking color photoresist films of 3 μm in thickness. As a result, higher UV exposure dosages are needed to obtain fully crosslinked colored SU-8 patterns. Different colored SU-8 photoresists can be patterned sequentially on the same substrate, as demonstrated by the fabrication of a five-color filter array. This work provides extensive details about the optical properties and the fabrication process of colored SU-8 photoresists, which, to the best of our knowledge, is currently lacking in existing literature. Our results can serve as a resource and starting point to apply this versatile material to future imaging and sensing applications.

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