Fabrication of PVA Micropolarizer Arrays for a CMOS Image Sensor

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ABSTRACT

Most image sensors ignore the polarity of light signals, primarily because the human eye is not sensitive to polarization. However, it is possible to gather valuable information about geometry and composition based on the polarity of light reflecting off of an object. A polarization sensor has been designed combining a CMOS image sensor with micropolarizers fabricated out of polarizing polyvinyl alcohol (PVA) sheets. This project was focused on fabricating these micropolarizers using photolithography and etching. In order to obtain complete characterization for each pixel, it is necessary to obtain the intensity of light polarized at 0 degrees, at 45 degrees, and in total. As a result, the micropolarizer array must contain two layers of 10-micron PVA structures oriented 45 degrees to each other. A single layer of micropolarizers was created in the PVA film using plasma etching, but exhibited significant etching underneath the structures created in the photoresist by lithography. A second etching technique, reactive ion etching (RIE), was evaluated and determined to cause significantly less underetching. Procedures for gluing layers of micropolarizers together and for removing the remaining photoresist were also developed. After a mask is fabricated with the proper alignment markers to allow layers of micropolarizers to be aligned relative to each other and to the CMOS chip, a complete polarization image sensor will be assembled using these techniques.

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1. INTRODUCTION

Polarization imaging is an emerging field with important applications in computer vision. Traditional image sensors are not built to be sensitive to polarization, focusing on other aspects such as color or total light intensity. However, the polarization of light reflecting off an object does carry useful information about the shape and composition of that object. This could allow computers to track objects, or robots to determine their own motion based on the movement of the scenery around them. The current generation of polarization sensors is dependent on bulky mechanically moving polarizing filters, limiting their usefulness. Viktor Gruev and Jan Van der Spiegel have designed a CMOS sensor that will be able to calculate the polarization parameters of natural light without mechanically moving filters, overcoming this limitation.

This project is focused on creating the micropolarizer array necessary to complete a CMOS image sensor. It is a continuation of a 2005 SUNFEST project carried out by Kejia Wu of the University of Pennsylvania which developed techniques to create a single layer of micropolarizers [1]. This project continues that work, and centers on preparing to fabricate the micropolarizers directly on the image sensor.

2. OVERVIEW OF POLARIZATION IMAGE SENSORS

2.1 Polarization[1]

The orientation of the electric fields of light is known as the polarization. There are numerous ways to represent this phenomenon mathematically, but one common form is the Stokes Vector. The Stokes Vector is composed of four elements: S_0 is the total intensity, S_1 is the degree of polarization at two perpendicular axes, S_2 is the degree of polarization at two perpendicular axes 45° to the right of the previous set, and S_3 is the degree of circular polarization. Circular polarization is a phenomenon uncommon in most light sources of interest, and is not sought in our application. These elements can be expressed as shown below:

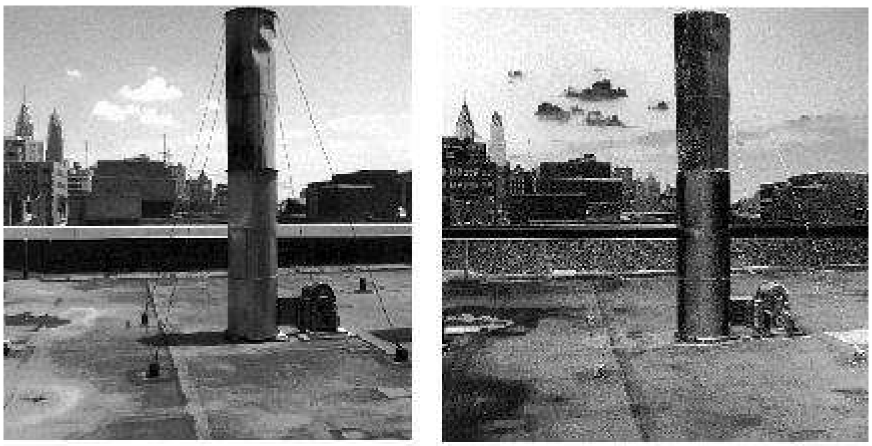
$$S_0 = I_{TOTAL}$$
$$S_1 = 2*I_0 - I_{TOTAL}$$
$$S_2 = 2*I_{45} - I_{TOTAL}$$
$$S_3 = I_{TOTAL} - 2*I_{45,\pi/2}$$

I_{TOTAL} is the total intensity of light, I_0 is the intensity of light polarized at 0 degrees, I_{45} is the intensity of light polarized at 45 degrees, and $I_{45,\pi/2}$ is the intensity of light polarized at 45 degrees after a phase shift of $\pi/2$.

[1] This overview of polarization was compiled with the help of [2] and [3]; for a more detailed presentation, refer to those sources.

2.2 Polarization Applications

The polarization of light varies significantly based on the composition of and angle of reflection off of an object. This has relevance in a number of different applications. Polarization filters are commonly used in sunglasses and photography to minimize glare. Past research has also been done to demonstrate a number of other applications of light polarization. Wolff and Boult [4] demonstrated that metals and dielectrics can be distinguished by the polarization of light reflected off of them; this could have valuable applications in computer vision and robotics. Figure 1 below shows one application of polarization imaging.



a) b)

Figure 1: The Philadelphia skyline a) as an intensity image, b) with the degree of polarization shown.

The picture on the left is a conventional grayscale picture of the Philadelphia skyline, using the intensity of light at each pixel. The picture on the right shows the same skyline using the degree of polarization. The pictures are very similar, but the polarization picture shows much better detail in areas of low light, such as the wall and in the shadow of the smokestack. Another important observation is the difference between the sky, which is uniformly polarized, and the clouds which exhibit random polarization.

2.3 Polarization Image Sensors

In the 1980s and early 1990s, most work on polarization imaging used polarization image sensors based on mechanically rotating filters in front of a standard camera (e.g. in [4]). These sensors were able to retrieve the polarization components from the incoming light, but tended to introduce optical distortions and required the polarization image frame rate to be significantly slower than that of the camera used. In 1995, Wolff and Andreou [5] introduced two alternative implementations of polarization imagers. The first technique used liquid crystals controlled by an electric field to replace the mechanically rotating polarization filter; this avoided some of the optical distortion effects of the rotating filter.

Their second technique was to use a beam splitter to divide orthogonal polarization components of the incoming light and direct that light onto two cameras. This allowed the sensing of polarization components, but required complicated optics and two distinct image sensor arrays. Our research is focused on a third technique proposed in [5]: this involves coating the image sensor directly with polarizing filters known as micropolarizers to retrieve the components of light polarized at 0° and 45°. Andreou and Kalayjian [6] and Momeni and Titus [7] implemented a polarization sensor using micropolarizers, but their sensor had much more limited resolution.

2.4 Micropolarizer Fabrication

Micropolarizer arrays can be fabricated with a variety of different techniques. One technique that has been used successfully in the past is to create micropolarizers using various structures in patterned metal. One research team successfully created micropolarizers using chromium strips fabricated on silica [8]. Another group has worked on the possibility that micropolarizers could be fabricated using columns of anodized alumina [9]. Micropolarizer effects could also be achieved with several other techniques. Research has been done developing micropolarizers by etching away segments of birefringent $CaCo_3$ crystal [10]. Another possibility that has been developed has been created using liquid crystal micropolarizers created on a thin gold film [11].

One of the most promising areas of micropolarizer research has been creating micropolarizer arrays using thin polymer-based polarized films. Junpeng Guo and David Brady [12] were able to create 5-micron pixel sizes using 1-micron thick film of a dichroic dye solution called Polacoat. Our goal is to create an array of filters using the more common PVA polarizer film, easily found in commercial polarizer filters. Guo and Brady [13] successfully have made dual-axes 25-micron structures in PVA; we would like to fabricate a micropolarizer array with structures as small as 10 microns.

2.5 Polarization Sensor Design

Our polarization image sensor is intended to obtain the first three Stokes parameters for every pixel. This requires the total light intensity and the intensities filtered with 0° and 45° polarization filters. Figure 2 below shows a simplified layout of the micropolarization pattern on the image sensor.

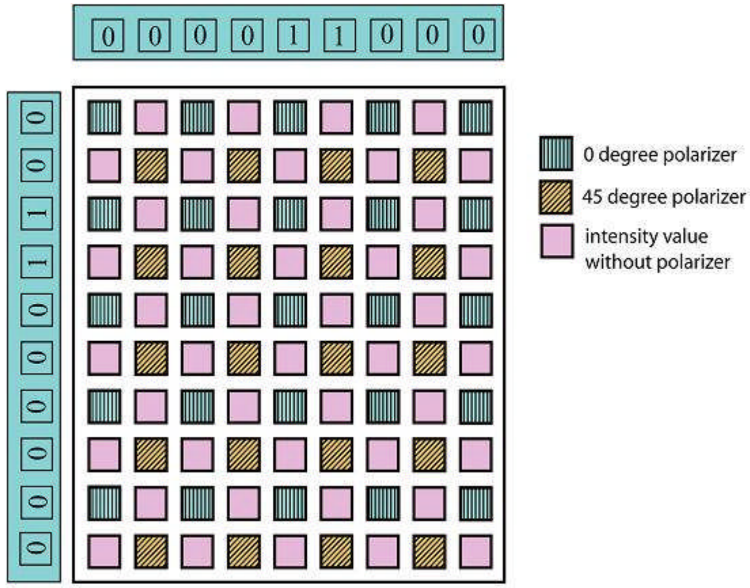


Figure 2: Layout of polarization image sensor.

As shown, each group of four adjacent photodiodes contains photosensitive elements below polarizing filters oriented at 0° and 45°, as well as two photosensitive elements without filters to obtain the total intensity at that pixel. By turning on two adjacent rows and two adjacent columns (denoted by 1's in the figure), the necessary components can be obtained to find the Stokes parameters at that pixel. In order to achieve this, two layers of micropolarizers oriented at 45 degrees to each other are required.

3. SINGLE LAYER MICROPOLARIZER FABRICATION

3.1 Sample Preparation

The first step in creating a micropolarizer array is to isolate the thin film of PVA in a commercial polarizing filter. Most commercial polarizing filters containing PVA use an arrangement similar to that shown in Figure 3 below.

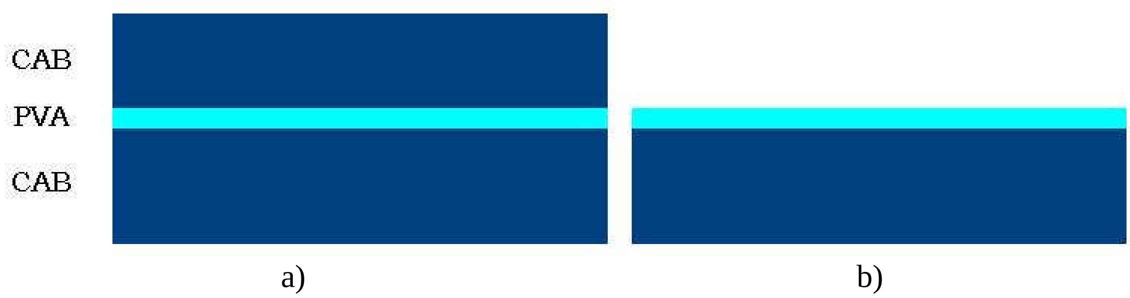


Figure 3: Commercial polarizing filter a) before and b) after the top CAB layer is removed.

A thin layer of PVA, generally about 20 microns thick, is sandwiched between two thicker (300 micron) layers of transparent backing material, in this case cellulose acetate butyrate (CAB). Since the micropolarizers need to be formed in the PVA layer, one of the two layers of CAB needs to be removed. The second CAB layer is left in place to provide backing; this is accomplished by protecting the back of the sample with chemical resistant tape. The top layer of CAB is then weakened by soaking the sample in acetone. The acetone attacks the CAB but does not react with the PVA film. Most of the CAB is removed by wiping it off the sample by hand. The final layers close to the PVA are dislodged using de-ionized water to avoid scratching the PVA.

3.2 Lithography

In order to create a layer of micropolarizers, the pattern must be printed on top of the PVA film using photolithography. First the PVA sample is cleaned with acetone to eliminate dust particles on the surface. A thin layer of a chemical called OmniCoat is then added to the surface of the PVA film. The OmniCoat is applied to the surface using a pipette, then accelerated to 500 revolutions per minute (RPM) over 5 seconds, then accelerated to 2000 RPM in 5 seconds and spun at 2000 RPM for 20 seconds. The OmniCoat serves two purposes. It improves the adhesion of the final photoresist structures to the PVA film by providing a better surface. OmniCoat also allows the photoresist structures to be removed more easily once the PVA film itself has been patterned. Next the sample is heated to 110° C for a period of 10 minutes to remove water from the PVA and to harden the OmniCoat layer. A thin layer of a substance known as a negative photoresist is deposited on top of the PVA; a negative photoresist is a substance that hardens when exposed to UV light, but can be easily removed in unexposed areas. A uniform layer of photoresist is made using spin coating. Photoresist is first added to the sample using a pipette. The sample is then spun at 500 revolutions per minute (RPM) for 10 seconds, then accelerated to 3000 RPM over 5 seconds, and spun at 3000 RPM for 45 seconds. The photoresist used was SU-8 2015, and based on the spin coating procedures, the SU-8 layer should be between 15 and 20 microns thick. Next the areas where the polarizers should be need to be exposed to UV light. This is done by covering with a mask the areas where the SU-8 should be removed, and then exposing the sample. A Karl Suss MA4 mask aligner was used for this purpose. The sample is exposed to 365 nm UV light at 8 mW/cm^2 for 25 seconds. The sample is then developed, removing the unexposed SU-8 and leaving the desired structures. Figure 4 below shows this process.

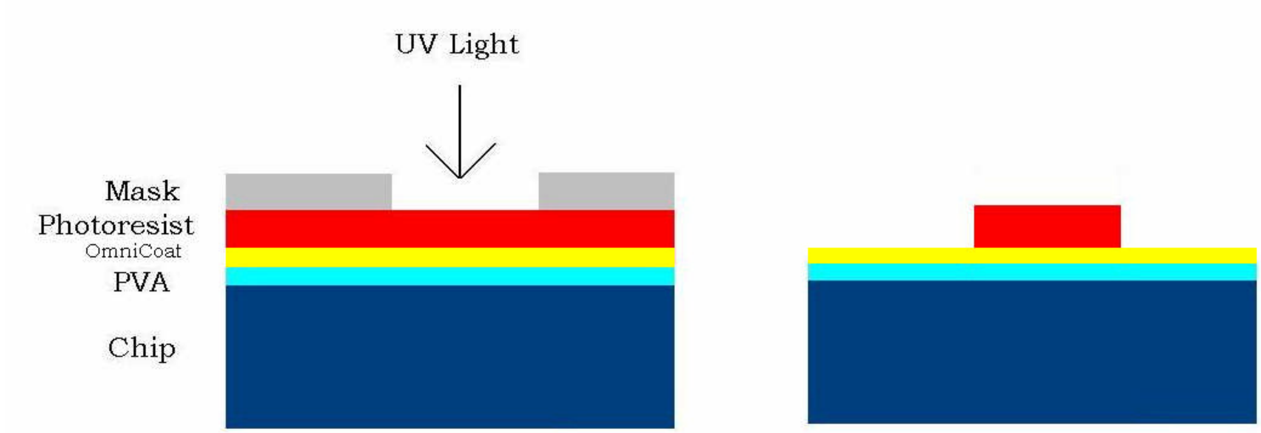


Figure 4: Photolithography step to define the pattern of the PVA to be etched.

3.3 Etching

Following lithography, there are SU-8 structures on top of the polarizing film; the next step is to create the micropolarizers themselves. This is done by removing the PVA in the areas not covered by photoresist in a process known as etching. Figure 5 below shows the etching process.

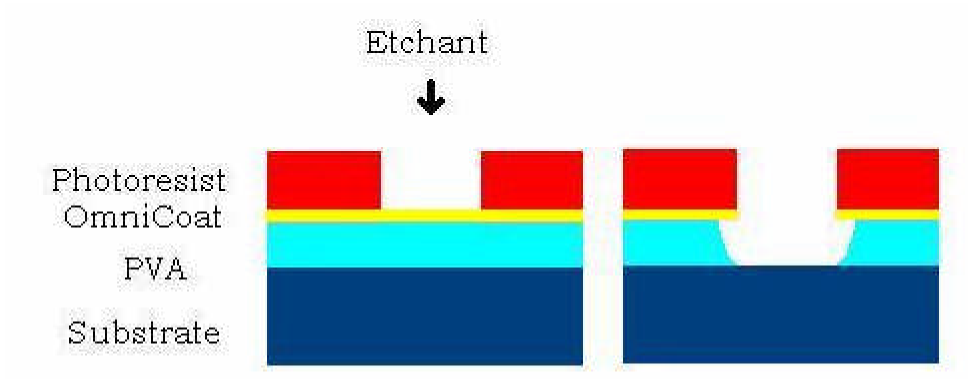
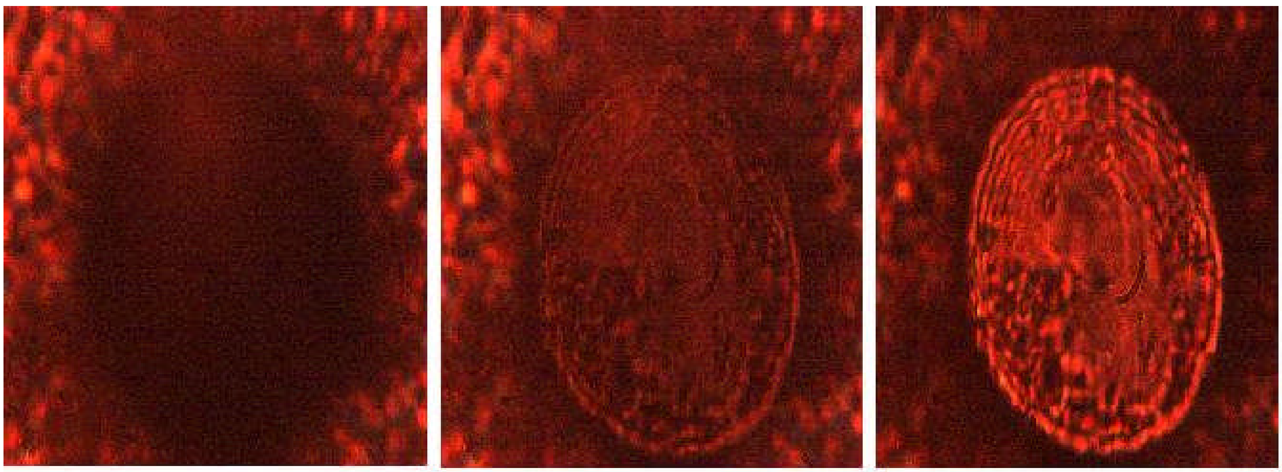


Figure 5: Etching process illustrating the concept of underetching

As shown, a substance known as an etchant is used to eat through the PVA, without attacking the photoresist layer. Depending on the etching procedure, a variety of etchant can be used. One common form of etching called wet etching uses a chemical such as an acid to remove the desired areas. This is not possible in this case, because wet etching removes the layer equally in both the horizontal and vertical directions. Since the PVA layer is 20 microns thick, and the desired structures are 10 micron, the structures would be destroyed in this process. An alternative technique called plasma etching uses high energy plasma to react with and remove the desired areas. This technique allows for sharper side walls, although there will be some degree of etching underneath the SU 8 structures, as shown in Figure 5. The OmniCoat is first developed (removed in the areas not covered by SU-8) by putting the sample in oxygen plasma for 90 seconds using a Technics PlasmaEtch II machine. The etching of the PVA is done with a mixture of oxygen and CF_4 in a three-to-one ratio using the same instrument. Another etching method being considered is reactive ion etching (RIE). RIE combines the oxygen plasma, which chemically reacts to etch away the PVA, with an equal concentration of high energy argon particles. Since argon is inert, it physically removes the PVA by hitting it at high speeds. This can be done by using a combination of oxygen and argon in the plasma etching machine.

3.4 Optical Properties

Initially, work was done with mask with a 15 micron circular pattern to develop the lithography and etching procedure and evaluate the resulting micropolarizers. Figure 6 below shows three images from a single micropolarizer as the incoming light shifts from being orthogonal to the polarizer to being parallel to the polarity of the polarizer.



a) b) c)

Figure 6: A single micropolarizer a) when incoming light is polarized at 90 degrees to the polarity of the polarizer, b) with incoming light at 45 degrees, c) with incoming light at 0 degrees

As shown in 6(a), when the light is orthogonal to the micropolarizer, very little light passes and the micropolarizer appears dark. At 45 degrees to the polarity of the micropolarizer, seen in 6(b), some light is able to pass, and the polarizer appears only slightly less bright than the background. In 6(c), the polarizer is at the same orientation as the incoming light, and the micropolarizer appears transparent. Figure 7 below shows the amount of light passing for each degree of polarization.

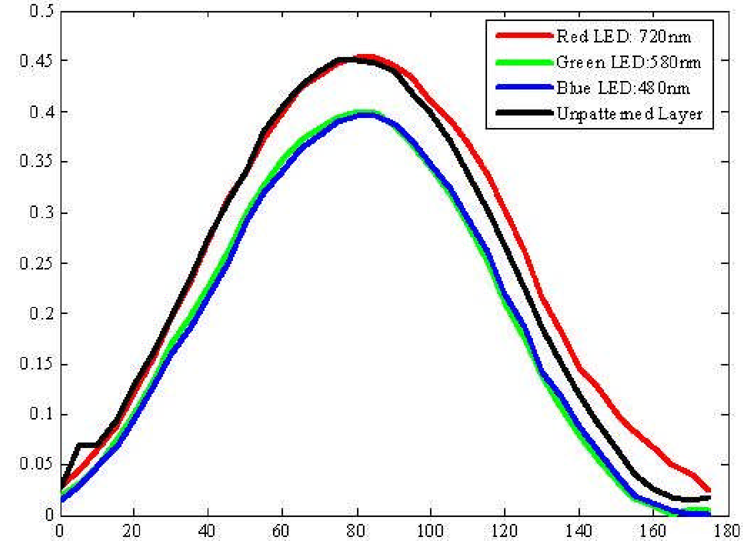
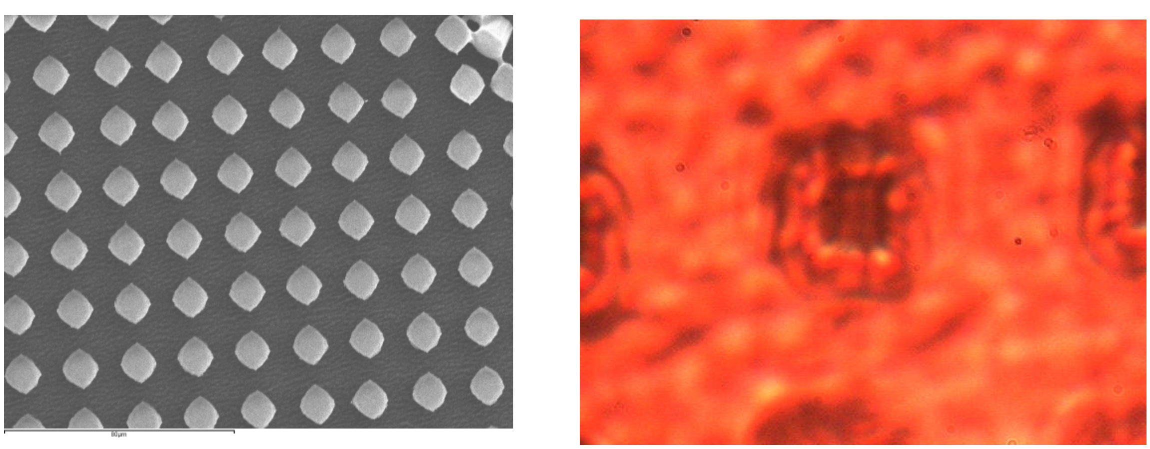


Figure 7: Graph of transmission percentage vs. polarization angle of light source

As indicated on Figure 7, the micropolarizer passes about 40% of light when aligned with the polarization angle of the light source, and less than 0.1% when orthogonal to that angle for both green and blue light. Longer wavelengths, such as red, pass at about 45% when aligned, and 3% when orthogonal. Hence, the extension ratio, defined as the ratio of the maximum to the minimum light intensity, is 100 for red light and 1000 for blue light. The black dotted line on the graph shows the characteristics of the unpatterned PVA film. We can conclude that the micropolarizer structures retain the polarization properties of the original unpatterned polarization filter.

3.5 Plasma Etching vs. RIE

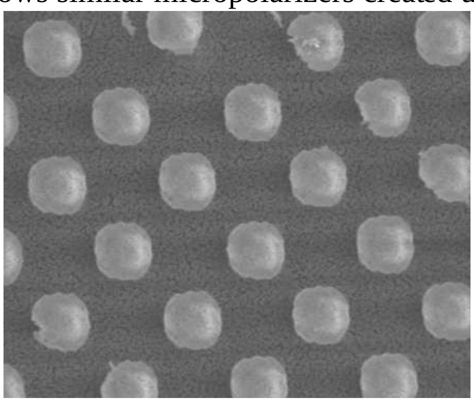
A second layer of micropolarizers was created using a mask that contains the pattern that will be needed for the final sensor. The micropolarizers were etched using the plasma etching technique. Figure 8 below shows this micropolarizer array.

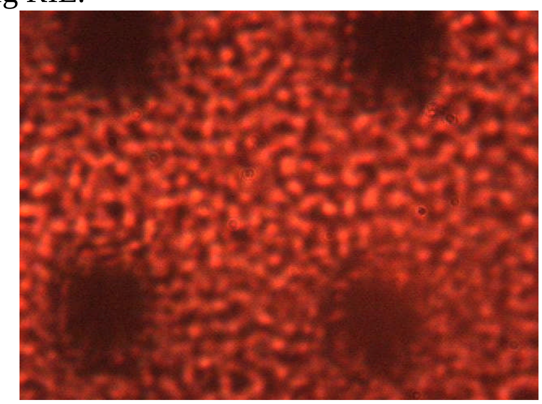


a) b)

Figure 8: Micropolarizers fabricated using plasma etching. a) A section of the micropolarizer array taken using a scanning electron microscope (SEM). b) A single micropolarizer at higher magnification using an optical microscope.

Figure 8a shows the structures created on the PVA imaged under a SEM. Every other space in each row and column is covered by a micropolarizer, as desired. Figure 8b shows a single micropolarizer at higher magnification imaged under an optical microscope. The larger transparent square is the SU-8 structure on top of the micropolarizer; the smaller dark square is the region that is actually polarized. A large percentage of the original pattern on the mask is lost due to underetching, approximately 3 microns on each side of the 12 micron structure. One possible method to avoid this problem is to compensate by creating a mask with larger features. The alternative is to switch to an alternative etching method such as reactive ion etching. Figure 9 below shows similar micropolarizers created using RIE.

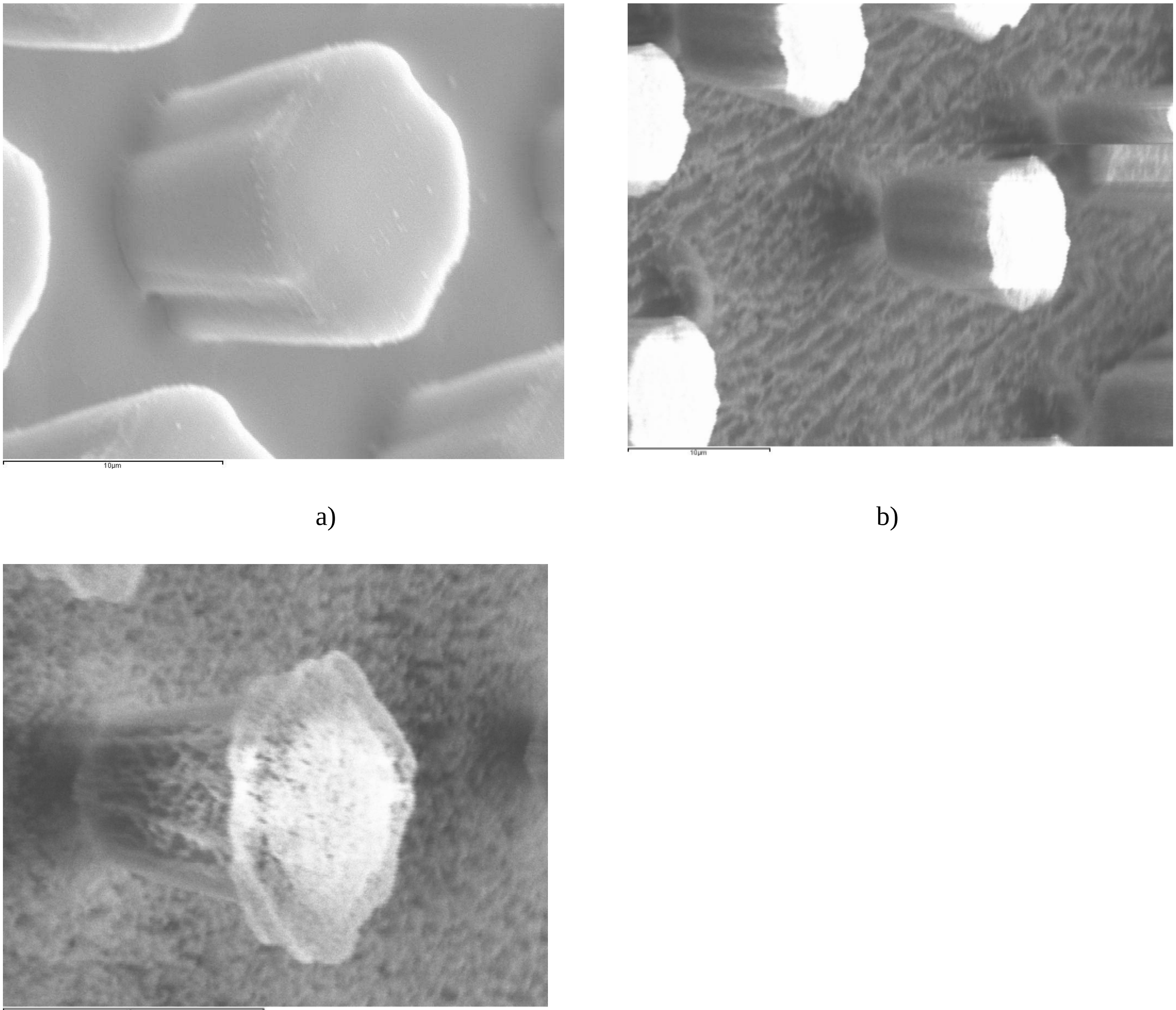




a) b)

Figure 9: Micropolarizers fabricated using plasma etching. a) A section of the micropolarizer array taken using an SEM. b) The array at higher magnification taken through an optical microscope.

Figure 9a shows the structures created on the PVA. Figure 9b shows a smaller group of the micropolarizers at higher magnification; the dark polarized area is much larger relative to the size of the overall structure. To better evaluate the level of underetching in each case, the structures were examined using a scanning electron microscope, as shown in Figure 10.



a) b)

c)

Figure 10: A single structure a) before etching, b) with plasma etching, and c) with reactive ion etching. The scale bar in each case is 10 microns.

Figure 10a shows a single structure after lithography; the height of the structure was measured to be approximately 14 microns, with a diameter of approximately 12 microns. 10b is a single micropolarizer etched using the plasma etching technique. The large structure on top is the SU-8, which is resistant to the plasma and remains mostly intact. The actual micropolarizer underneath is much smaller, as shown by the small root-like structure underneath the SU-8. 10c is a micropolarizer created using RIE; the SU-8 structure is nearly destroyed, since the argon attacks it as well as the PVA. However, the actual micropolarizer is nearly as large as the original SU-8 structure; the underetching is much smaller, approximately one micron on each side. The grainy appearance of the structure in 10c is due to the RIE; the argon tends to damage the surface of the structures. This may degrade the optical properties; this is still being evaluated.

4. DOUBLE LAYER MICROPOLARIZER ARRAYS

4.1 Methods for Gluing Multiple Layers

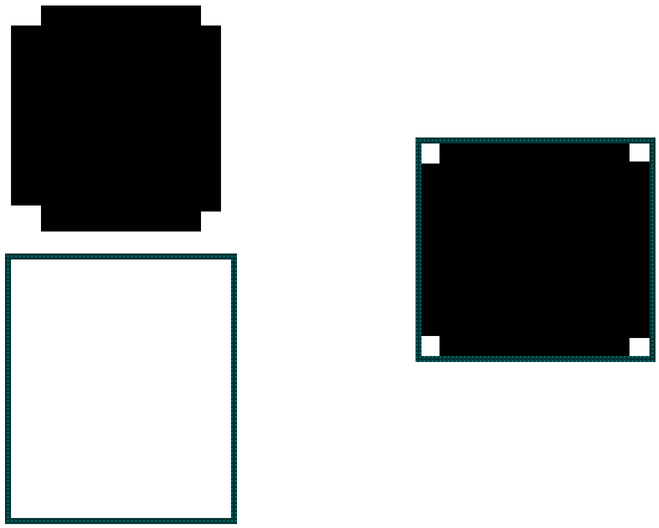
In order to create the required micropolarizer array, a method to create micropolarizers directly on the image sensor is required. Previously the micropolarizers were created using the CAB layer as backing material. Since the CAB layer is 300 microns thick, this layer would decrease the light transmission rate as well as introduce undesirable optical distortions. As a result, we would like the PVA to be glued directly onto the image sensor, allowing the removal of CAB using acetone.

Initially this was attempted using SU-8, our photoresist, as an adhesive. SU-8 is an epoxy based chemical, similar to many glues, and will stick to PVA. It will also adhere to the SiO_2 that forms the top surface of the CMOS image sensor, based on experimentation using glass. However, gluing with SU-8 requires that the solvents within the SU-8 evaporate, allowing the photoresist to harden. In this case, the SU-8 is sandwiched between the chip and the PVA, limiting the evaporation and leading to a poor bond between the layers.

To avoid this, the process was repeated using an optical glue from Dymax called OP-30. OP-30 is a UV curing adhesive that contains no solvents; it hardens completely upon exposure for a short period of time to UV light. This allowed the sample to be glued by administering the glue, placing it under a glass plate, and exposing it using the mask aligner. The mask aligner also allowed the application of pressure to press out air bubbles in the glue. Upon attempting to remove the CAB layer, however, the acetone tended to attack the OP-30, destroying the bond. A second UV curing glue, Loctite 349, was then tested and determined to have similar difficulties with acetone. Since the acetone is only able to attack the small boundary areas of the glue, it may be possible to overcome this problem by protecting these boundaries with chemical resistant tape or by using large samples and cutting out the areas lost due to acetone. An acetone resistant two part epoxy, Loctite E30CL, was tested as well, but was found to have difficulties evaporating solvents similar to the problems with the SU-8.

4.2 Aligning Multiple Layers

For the micropolarizer array to be useful, the micropolarizer on each layer need to be placed in the proper locations relative to each other and the image sensor. This can be done using the optics on the mask aligner, but some points of reference on each layer are required. This is traditionally done using elements known as alignment markers. Figure 11 below shows a basic alignment marker system.



a) b)

Figure 11: Traditional alignment markers. a) The shapes of two simple alignment markers. b) The appearance of the markers when brought into the proper alignment

As shown, the traditional alignment marker system is a cross and a square. When placing a layer, the person aligning places the cross within the box created by the square. The cross and square system work particularly well because it allows the person aligning to not only place a point on the two layers relative to each other, but also enables the person to achieve the proper angle of rotation to achieve the proper alignment. Our image sensor does not contain any specific alignment markers, but the large square input and output pads can be used for that purpose. The alignment marks on the final mask will have to be placed to allow this use.

4.3 SU-8 Removal

Although SU-8 is mostly transparent, the 15-20 micron thick photoresist structures tend to attenuate light to some degree. As a result, the photoresist should be removed after etching the PVA to create the micropolarizers. SU-8 generally bonds strongly after photolithography but the layer of OmniCoat does allow its removal. The samples can be dipped in an 85° C bath of a chemical called Remover PG for 30 minutes to remove the photoresist. This procedure has been used to remove SU-8 structures successfully from a glass slide. Since Remover PG attacks the CAB substrate of the PVA structures, this has not been completed with an actual micropolarizer array. Another possibility is to remove the SU-8 during etching. In reactive ion etching, the argon attacks the SU-8, as shown in Figure 10c. By changing the spin acceleration to change the thickness of photoresist, this can be used to eliminate the SU-8 as well. The CF_4 and oxygen mixture does not attack the SU-8, as shown in Figure 10b, so this would not be possible for plasma etching.

5. DISCUSSION AND CONCLUSIONS

Polarization image sensors are an exciting new development with numerous possible applications. Thin film micropolarizer arrays will be necessary to make polarization sensors practical. An effective technique for fabricating a single layer of 10-micron micropolarizers in thin polyvinyl alcohol film has been presented. The micropolarizers were demonstrated to have a transmission rate similar to that of the original polarizing film; they can, therefore, be used effectively in a polarization image sensor. Two different etching techniques, plasma etching and reactive ion etching, are evaluated. Plasma etching was found to cause a large degree of etching underneath the photoresist structures, degrading the quality of the micropolarizers formed. Reactive ion etching, however, was found to cause significantly less underetching, maintaining most of the 10 micron structures formed in the photoresist. Reactive ion etching was also found to remove most of the photoresist from the polarizer, unlike the plasma etching technique. As a result, the reactive ion etching will be used in the final polarization sensor. This paper also presents preliminary work towards fabrication of a multiple layer micropolarizer array.

6. RECOMMENDATIONS

Microfabrication is a delicate procedure that is extremely sensitive to environmental conditions. Many of the difficulties encountered can be mitigated or even eliminated with better-controlled temperature and lower humidity. As a result, my primary recommendation is to repeat some of the more promising efforts outside of the warm summer months; this has great potential to help improve our results. Future work should be devoted towards expanding on the efforts toward creating a multi-layer micropolarizer array. A new mask should be designed and fabricated using the proper alignment markers so that it can be used for multiple layers.

7. ACKNOWLEDGMENTS

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