Integrated High Resolution Focal-Plane Polarization Imager

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ABSTRACT

The polarimetric vector is a more general descriptor of light than intensity information alone, and it contains physical information about the imaged objects in a scene that traditional intensity based sensors ignore. Polarimeters – devices that measure polarization – are used to extract physical features from an image such as specularities, occluding contours, and material properties. Scientists use polarization information to perform difficult tasks such as image segmentation and surface reconstruction, object orientation, material classification, atmospheric and solar analysis. We will present an integrated CMOS sensor/imager that uses a unique polymer-based polarizing filter to sense two orthogonal directions of linear polarization. The CMOS imager uses analog translinear circuitry to compute, in real-time on the focal-plane, polarization contrast: a measure of the orientation and degree of linear polarization in an imaged scene. We will present the microfabrication technique that enables us to apply CMOS fabrication technology to bulk manufactured poly(vinyl alcohol) linearly polarizing films. This technique allows us to define lithographically micron-scale linearly polarizing regions in polymer-based polarizing filters in order to make a high resolution polarization contrast imager.

POLARIZATION CONTRAST

The electric field (e-vector) of electromagnetic waves can be expressed as the superposition of two orthogonal components, E_x and E_y, and can be written as

$$\vec{\mathbf{E}} = \hat{x}E_x e^{-j(\omega t - kz)} + \hat{y}E_y e^{-j(\omega t - kz + \varphi)}, \qquad (1)$$

where ω is angular frequency, k is the wave-vector, and φ is the phase between the orthogonal electric field components. If the phase is deterministic and φ=0, light is *linearly* polarized; in the case of φ≠0, light is *elliptically* polarized. While polarized light sources are rare in nature, reflected or scattered light is almost always partially linearly polarized, which means that it has an unpolarized component and a linearly polarized component.

Intensity based imagers, such as CCD cameras and Active Pixel Sensors[1] cannot distinguish between polarized and non-polarized light, and therefore lump the orthogonal e-vector components into one intensity term by summing the energies of E_x and E_y. Our *polarization contrast imager* analyzes the orthogonal electric field components of incident light at the pixel level and can image temporal and spatial polarization changes in a scene. Since the degree and orientation of polarization of reflected or scattered light is intimately related to the physical properties of the reflecting or scattering object (especially its surface properties, index of refraction, and spatial orientation), our polarization imager can offer physical cues which intensity or color imagers neglect. Below, we will show how polarization information can be used to obtain shape information in an imaged scene. This type of operation is important in the field of image understanding and object recognition.[2][3][4]

We define *polarization contrast* using the following equation:

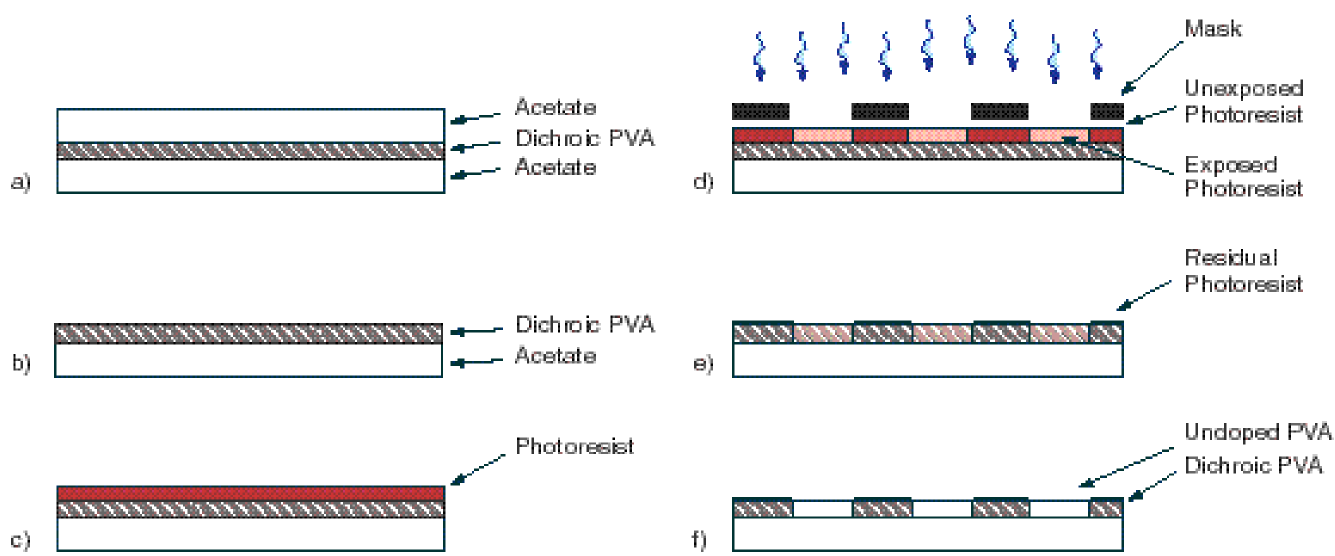

Figure 1. Lithography on the polarizing polymer film poly(vinyl alcohol) (PVA). a) Cross-section of a typical dichroic PVA polarizer, b) Acetone is used to dissolve the acetate layer on one side to expose dichroic PVA, c) Photoresist is spun on to PVA, d) Photoresist is exposed to UV light through a chrome mask, e) As the photoresist is developed, iodine begins to dissolve from the PVA. After 1 minute in the developer solution, only a residual layer of unexposed photoresist remains, f) After 2 minutes in the developer, iodine is completely dissolved from the PVA, leaving a micron-scale pattern of polarizing and non-polarizing PVA.

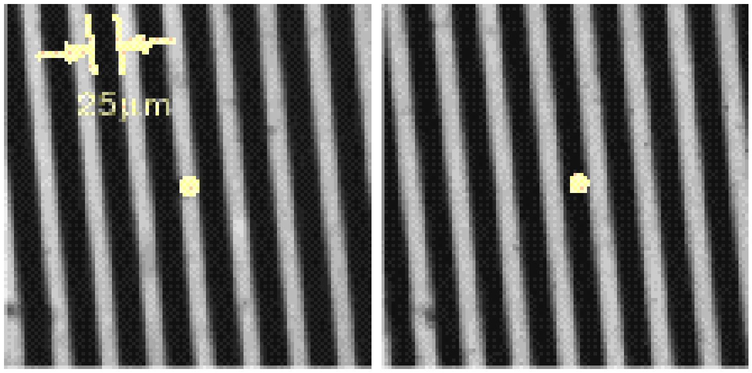

Figure 2. Photomicrograph of focal-plane polarizing filter. Two linearly polarizing polymer (PVA) films with alternating transparent and polarizing lines are aligned to form one focal-plane polarizer filter. This photomicrograph shows two views of the same filter with the microscope polarizer set at 0º (left) and 90º (right). The white dot is provided as a stationary point of reference.

$$\textit{polarization contrast} = \frac{TR \quad - TR_{\parallel}}{TR \quad + TR_{\parallel}}, \qquad (2)$$

where $TR_{\parallel}$ and TR represent the transmitted radiances through orthogonal linear polarizers whose transmission axes are orthogonal relative to each other. Polarization contrast is a relative measure of the degree and orientation of linear polarization in a scene.[5] In the following sections, we describe how we extract orthogonal polarization components at the pixel level using specially processed linearly polarizing dichroic polymer film. We also describe a custom fabricated CMOS imager that uses translinear circuits to compute polarization contrast.

PVA FILM LITHOGRAPHY

Linearly polarizing films – iodine doped poly(vinyl alcohol) (PVA) dichroic films in particular – are manufactured through a bulk process that is not amenable to delineating micron-scale features. The manufacturing process for a widely used polarizing film, the H-sheet, dissolves potassium-iodine solution into a sheet of poly(vinyl alcohol) (PVA).[6] When the iodine-doped PVA is stretched, the polymer chains of PVA are axially coordinated along the stretching direction. Stretching of the PVA film causes an abundance of polyiodine complexes of I_3^- and I_5^- to form in linear chains that lie parallel to the polymer molecules. These conducting complexes form a light-absorbing axis in the entire film along the stretching direction, imparting dichroism to the otherwise transparent polymer sheet. We have developed a lithographic process to fabricate a linearly polarizing focal-plane filter suitable for a high resolution CMOS imager using commercially available, bulk-manufactured PVA films. The technique uses masking and 'etching' steps similar to those in VLSI silicon fabrication processes to *undope* selectively the iodine complexes which impart dichroism to the otherwise transparent PVA.

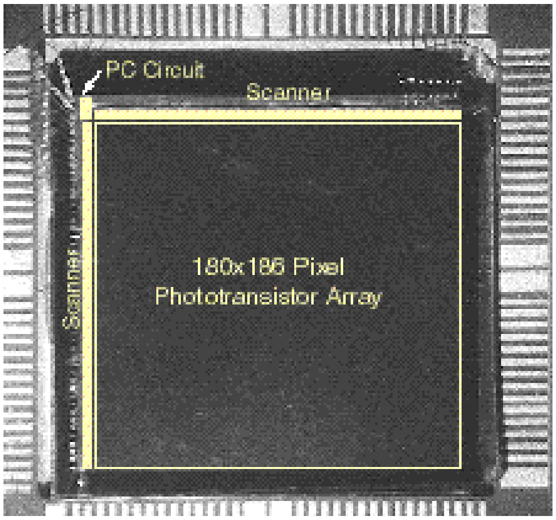

Figure 3. Photomicrograph of polarization contrast imager.

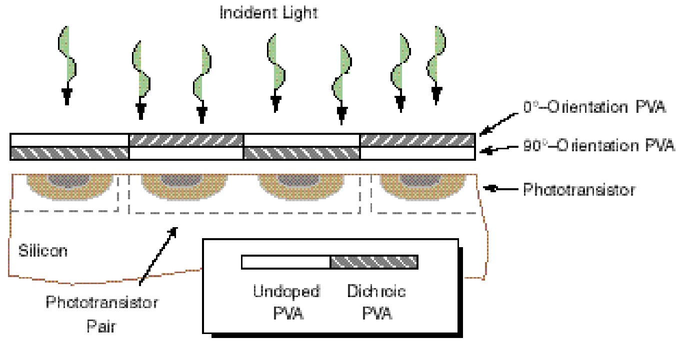

Figure 4: Two linearly polarizing films are lithographically processed and aligned to a CMOS imager so that alternating phototransistors receive light through orthogonal polarizers.

Our process begins with a commercially available H-sheet (Figure 1), which consists of a thin layer of PVA sandwiched between protective sheets of clear cellulose acetate. Acetone dissolves the protective acetate layer to expose the dichroic PVA. Photoresist is then spun on the PVA, baked and exposed through a lithographic mask. As the photoresist is developed, the basic developer solution also dissolves, or undopes, the iodine from the PVA layer, but only underneath areas of exposed photoresist. By removing the iodine complexes in areas defined photolithographically, we create a polarizing film with micron-scale polarizing regions separated by clear, non-polarizing PVA.

For our polarization contrast imager, we stack two orthogonal polarizers that have been processed in this fashion such that regions of dichroic PVA in one polarizer lie underneath regions of undoped PVA in the other. Thus, we create a linearly polarizing filter with spatially varying transmission-axis orientations at a 25μm spatial frequency. Figure 2 shows a photomicrograph of the focal-plane filter we used for the polarization contrast imager.

POLARIZATION CONTRAST IMAGER

The custom CMOS imager comprises an 180x186 array of phototransistor pairs, scanning circuitry, and an analog circuit that computes polarization contrast fabricated in a standard 1.2μm n-well CMOS process (Figure 3). The polarizing focal-plane filter described in the previous section is aligned with the array so that each phototransistor in a pair lies underneath orthogonal linear polarizers as shown in the schematic diagram in Figure 4. Each phototransistor in a given pair receives the transmitted radiance through a linear polarizer orthogonal with respect to its twin.

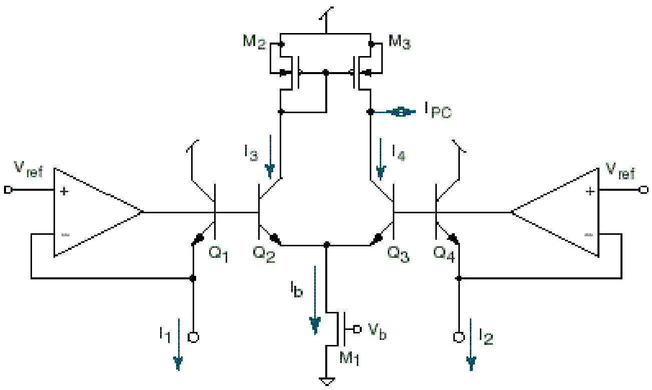

Figure 5. This translinear circuit computes *polarization contrast*. $I_{pc} = I_b * (I_1-I_2) / (I_1+I_2)$

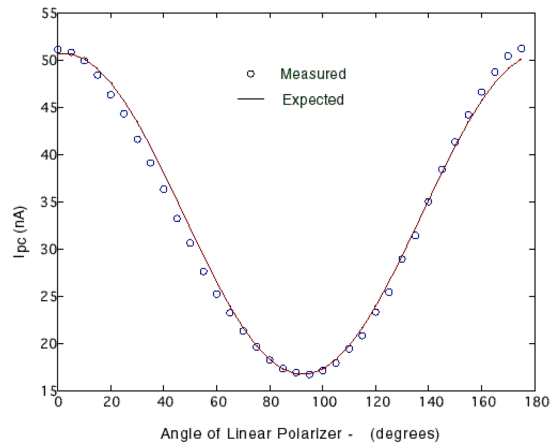

Figure 6. Response of polarization contrast circuit to a linear polarizer at different angles.

The array is addressed so that the photogenerated current of the two phototransistors in a selected pair are routed to individual video amplifiers and to an analog circuit that computes polarization contrast (Figure 5). The circuit operates on the two currents, which are proportional to the transmitted radiances through the orthogonal polarizers, and produces one output current that represents the polarization contrast, I_{PC}.

The analog, current-mode circuit that computes polarization is implemented with bipolar transistors for improved precision. Using the translinear principle[7], we can show that

$$I_{PC} = I_b \frac{I_1 - I_2}{I_2 + I_1}, \qquad (3)$$

which is a scaled version of the polarization contrast, since the currents I_1 and I_2 are directly proportional to the transmitted radiances $TR_{\parallel}$ and TR .

RESULTS

Figure 6 shows the response of the contrast circuit using a two-pixel test circuit.[8] We placed a linear polarizer in front of the sensors and rotated it through 180° while measuring I_{PC} every 5°. The angular measure, θ, of the linear polarizer is given with respect to the 0°-orientation of the polarizing film on the chip. Since the transmitted radiance of linearly polarized light through a linear polarizer varies sinusoidally with the polarizer angle (with a period of 180°), the expected current output from the phototransistors is:

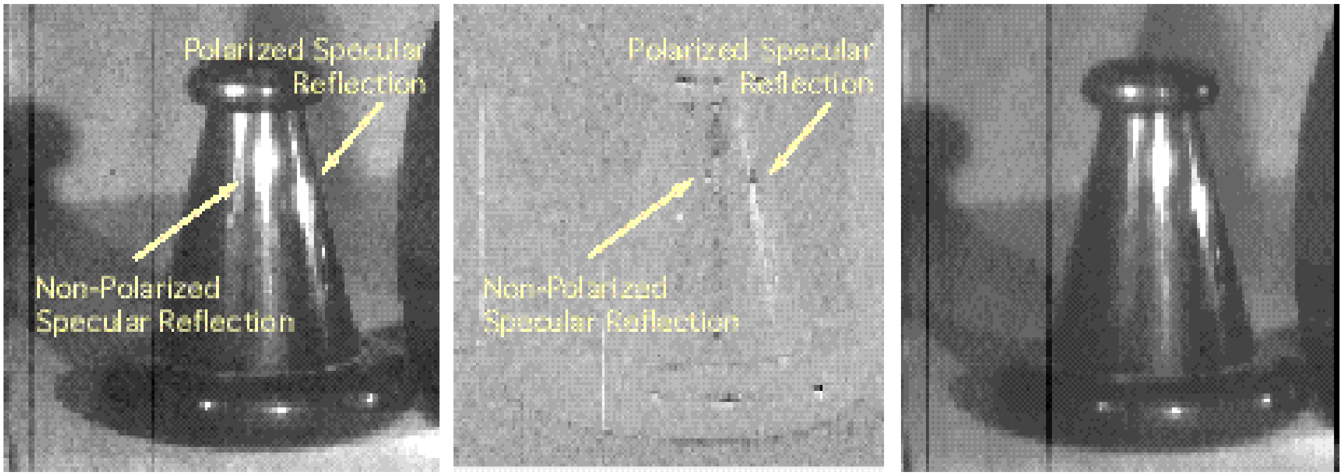

Figure 7. This captured output shows how the polarization contrast imager can distinguish between different angles of specular reflection. Center: Polarization contrast image. Left and right: Transmitted radiance images through orthogonal polarizers on the focal plane. Vertical stripes are due to polarizing filter irregularities.

$$I_1 \sim 1 - Cos(2\theta) \qquad (4)$$

$$I_2 \sim 1 + Cos(2\theta). \qquad (5)$$

Substituting into Equation 3 yields

$$I_{PC} \sim Cos(2\theta), \qquad (6)$$

which is shown as the solid curve in Figure 6.

Figure 7 shows a set of images produced by the imager: the center figure is the polarization contrast image, and the two flanking images represent $TR_{\|}$ and TR of the scene. The cone-shaped object is made of black plastic and is illuminated by point sources from two directions – head on and laterally. In the TR images, two similar looking high intensity regions are visible. These bright regions of the image, which appear identical to the naked eye or to a normal video camera, carry physical information about the object which can be useful in determining the object's shape or composition.

Maxwell's equations require that the tangential electric and normal magnetic fields must be continuous across a boundary. The polarization of reflected light will be determined by these boundary condition and will depend on the angle of incidence and the material properties of the reflecting object. The ratio of the polarized component to the total intensity, the *degree of polarization*, can be written in terms of the Fresnel reflectance coefficients for the perpendicular and parallel components of the incident radiation (with respect to the plane of incidence):

$$\text{degree of polarization} = \frac{R_\perp^2 - R_\parallel^2}{R_\perp^2 + R_\parallel^2} \qquad (7)$$

$$R_\perp = \frac{n_1 \cos\theta_i - n_2\sqrt{1-\frac{n_1^2}{n_2^2}\sin^2\theta_i}}{n_1 \cos\theta_i + n_2\sqrt{1-\frac{n_1^2}{n_2^2}\sin^2\theta_i}} \qquad (8)$$

$$R_\parallel = \frac{-n_2 \cos\theta_i + n_1\sqrt{1-\frac{n_1^2}{n_2^2}\sin^2\theta_i}}{n_2 \cos\theta_i + n_1\sqrt{1-\frac{n_1^2}{n_2^2}\sin^2\theta_i}} \qquad (9)$$

where *n* is the simple index of refraction (only a lossless, linear, and homogeneous medium is considered here) and θ_i is the angle of incidence with respect to the surface normal.

In Figure 8, the degree of polarization versus the angle of incidence is graphed according to equations 7-9. The figure shows that at most angles of incidence, measured from the surface normal, light becomes polarized perpendicular to the plane of incidence. At one angle, light is completely polarized perpendicular to the plane of incidence; this angle is known as *Brewster's Angle*, and depends on the dielectric properties at the reflecting interface.

The center image in Figure 7 shows that the polarization contrast imager differentiates between the two

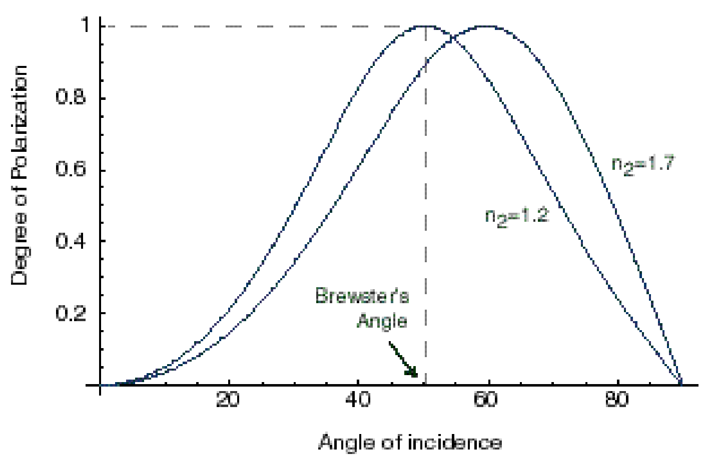

Figure 8. Degree of polarization vs. angle of incidence. Specularly reflected light is completely linearly polarized perpendicular to the plane of incidence at *Brewster's Angle*.

specular reflections, which are incident on the object at different angles. This information can serve as an important cue when characterizing the shape of an object in a scene. Alternatively, if shape information is already known, as might be the case in an assembly line, the degree of polarization could be used to assess the dielectric properties of objects in an imaged scene. The dielectric constant can be calculated by finding Brewster's angle, which is the maximally polarized region in the image. Since the imager is sensitive to the physical processes associated with reflected light, it can be used to glean information about a scene that is absent from intensity and color images.

DISCUSSION

Our polarization contrast imager is the world's first integrated high resolution focal-plane polarization imager. We have shown how to process commercially available linearly polarizing films to make high resolution polarization filters suitable for a CMOS camera using VLSI circuit fabrication techniques. We described how a film processed in this fashion is mounted on a custom made CMOS imager to make a polarization contrast imager. The CMOS imager we built uses analog translinear circuitry to compute polarization contrast at the pixel level and simultaneously outputs three video images: two intensity images corresponding to the transmitted radiance through orthogonal polarizers, and a third image representing polarization contrast, which is a measure of the degree and angle of polarization in a scene.

We demonstrated our polarization contrast camera by looking at an image that contained specular reflections at different angles on the same object. Since the polarization of reflected light is dependant on the angle of incidence and on the material properties of the reflecting object, the polarization state of reflected light can be used to characterize the shape of an object or its material composition. Our polarization imager is sensitive to physical information in a scene that intensity and color imagers cannot see.

Polarization sensitivity is found among many terrestrial and marine invertebrates and some species of fish. Polarization contrast vision in the octopus is thought to provide an additional visual cue to enhance detection and recognition of objects.[9]

ACKNOWLEDGEMENT

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