INTEGRATED POLARIZATION-ANALYZING CMOS IMAGE SENSOR

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Abstract— **A CMOS image sensor with an integrated wire grid polarizer to sense the polarization of light is presented. The chip consists of an array of 128 by 128 pixels, it occupies an area of 5x4 mm^2 and it has been designed and fabricated in a CMOS 180nm process. Extinction ratio of 6.3 and 7.7 were achieved. The sensor is used to classify materials based on the degree of polarization and the transmitted intensity after specular reflection on the material surface. The variation in the transmitted intensity among dielectrics and metals was successfully demonstrated.**

I. Introduction

The three basic characteristics of light are intensity, color and polarization. Polarization provides a more general description of light than either the intensity or the color alone, and can therefore provide richer sets of descriptive physical constraints for the interpretation of the imaged scene.

Polarization information can simplify some visual tasks (e.g. region and edge segmentation, material classification etc.) which are more complicated or practically infeasible when limited to intensity and color processing. Polarization can also be used to classify chemical isomers [1], to analyze reflections [2], to classify materials based on the specular reflectivity [3], [4] and for biomedical imaging [5]

State of the art polarization image sensors consist of a photodetector array, such as a CMOS or a CCD sensor array, and a single or multiaxis micropolarizer array to measure the polarization information in real time [6], [7], [8], [9]. These polarization image sensors work either in time domain multiplexed mode or in spatial domain multiplexed mode. In time domain multiplexed mode a linear polarization filter is rotated in front of either a single photodetector or a complete photodetecor array. The disadvantages of time domain multiplexed mode are that a mechanical rotation of the polarizer filter is required and it also increases the frame time by the total number of orientation measurements desired. In case of spatial domain multiplexed mode, linear polarizers are oriented in different directions with respect to the photodiodes. The spatial orientation of the linear polarizer filter suffers from a reduced spatial resolution.

The micropolarizer can either be fabricated directly on the sensor array or can be fabricated on a substrate and flip chip bonded with the sensor array. Micropolarizers can be made either from organic materials [6], [9] or using metallic wire grid [8]. A micropolarizer created using an organic material would need additional fabrication steps, while the metallic wire grid micropolarizer can be made using the metal layers available with the standard CMOS technology.

From the aperture theory [10], [11], it is known that for an electromagnetic wave to be absorbed by a wire grid, its wavelength should be larger than the pitch of the wire grid ($\lambda/d>2$; where λ is the wavelength and d is the spacing between the wire grid). The visible spectrum wavelengths range from 300 to 720nm and thus a wire grid pitch of less than 300nm is desired. With the scaling of CMOS technologies, the distance between metal layers also scales, opening up the possibility of using them in a grid structure for the absorption of electromagnetic waves.

An embedded wire grid polarizer with an extinction ratio of 2.03, using a wire grid pitch of 1.2µm has already been demonstrated [8]. A higher extinction ratio of nearly 100 has been presented using organic micropolarizer with a pixel pitch of 10µm x 10µm [6]. An integrated polymer polarization filter array with a pitch of 6µm has been also reported [9].

Classifying materials into dielectrics or metals is an important application for scene analysis in computer vision. The light is partially polarized after reflection from the material surface [3], [4]. CMOS/CCD image sensors with externally controlled polarization filter have been used to demonstrate the differential reflection patterns of the metal and dielectric surface. The main disadvantage of such a system is that the linear polarization filters have to be controlled externally.

In this work we present a CMOS image sensor with real time polarization sensing ability. We also demonstrate the differential reflection behavior when light reflects from the metal and dielectric surface. Section II describes the image sensor with polarization sense regions formed with metal wire grids. In section III measurements results of the sensor are presented. The transmitted irradiances after reflection from the plastic and aluminum metal surface are also presented. The variation in the oscillation of the transmitted irradiance can serve as a model to classify materials into metals or dielectrics.

II. Sensor description

The image sensor consists of an array of 128 by 128 pixels, it occupies an area of 5 x 4 mm^2 and it has been designed and fabricated in the 180nm CMOS CIS process from UMC. The polarization sensing sensor has an embedded linear wire grid polarizer in each pixel, realized with the first metal layer of the process on top of a pinned photodiode (p^+/n^-/p-sub). The linear wire grid polarizer was implemented using thin metal strips with a line/space of 240nm/240nm (pitch of 480nm) as shown in Figure 1. Though a pitch of less than 300nm is required to cover the complete visible spectrum wavelength range, the chosen technology allows only for a pitch of 480nm. This is still an improvement over [11] where an external linear polarizer was used and [8] where the wire grid pitch was 1.2µm.

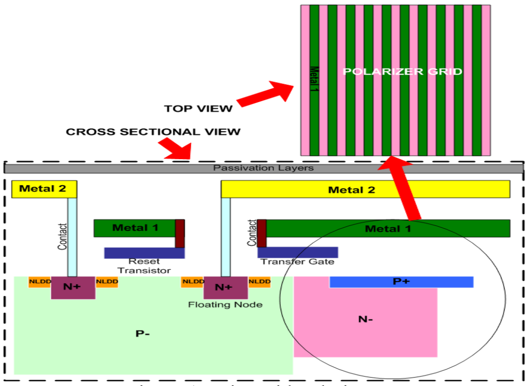

Figure 1: Wire grid Polarizer

The sensor specifications are shown in table 1.

TABLE 1: Sensor specifications

Process	0.18µm 1 poly 3 metals UMC CIS process
On-chip Polarizer	Line/Space = 0.24µm/ 0.24µm (0.48µm pitch)
Active imager size	3.2 mm(H) x 3.2 mm(V)
Chip Size	4 mm(H) x 5 mm(V)
Active pixels	128 x 128
Pixel size	25µm x 25µm
Shutter type	Global shutter
Maximum data rate/master clock	64 MPS / 32 MHz
Supply voltage	1.8V

Figure 2 shows the sensor architecture, and figure 3 shows some sample images from the image sensor. The chip is divided into four main blocks. First, the pixel array with the photodiodes and the associated circuitry for analog computations, which occupies most of the chip area. Each pixel contains a pinned photodiode and 32 transistors to perform low level image processing. The size of the photodiode is 10µm x 10µm which corresponds to a 16% pixel fill factor. In this paper we focus on the polarization sensing ability of the sensor and thus the low level image processing will not be discussed. Second, placed below the pixel array is the analog readout circuit. The analog readout circuit consists of column level circuits (double differential sampling circuit), an output amplifier, a buffer and the column shift register. The analog output provides the analog voltage at each pixel. Third, placed at the top is the digital readout circuit. The digital readout circuit consists of a 7-bit counter and a column shift register. The 7-bit counter is used to count the number of active high pixels in each row. Finally, the left side is dedicated to a row select logic and timing control blocks to address each row of pixels sequentially.

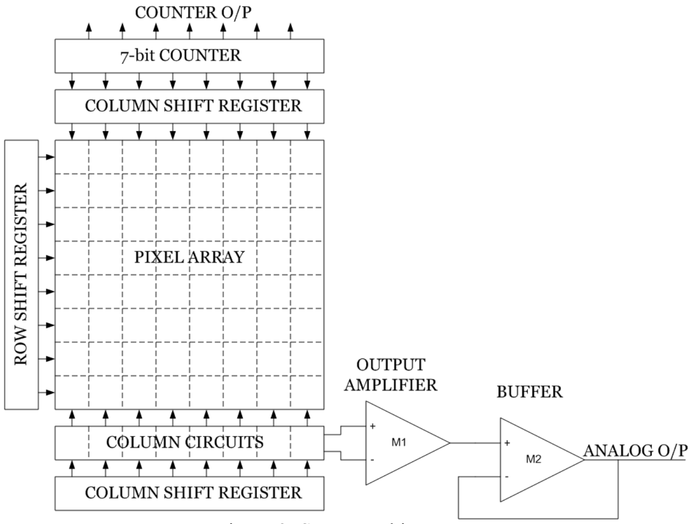

Figure 2: Sensor architecture

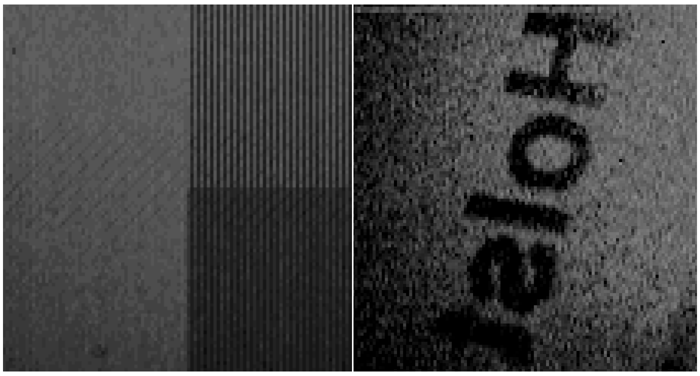

Figure 3: Sample images (left) transmission photograph of wire grid line array (right) Holst text

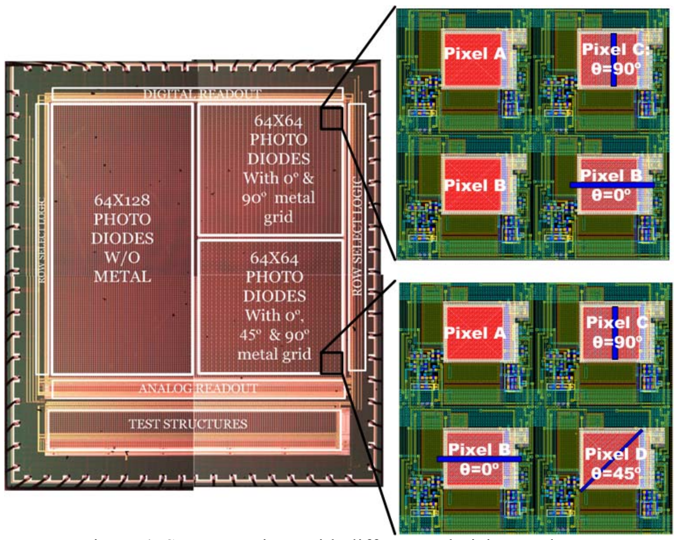

Figure 4: Sensor Regions with different Polarizing angles

The array of 128 by 128 pixels was split into three regions as shown in figure 4:

1. A 64x128 array without a metal grid used for normal imaging applications.

2. A 64x64 array (sense region 1) consisting of 2 by 2 pixel arrays where two pixels (A and B) measure the intensity while the other two measure the 0º (D), and 90º (C) degree polarized intensity respectively.
3. A 64x64 array (sense region 2) consisting of 2 by 2 pixel arrays where one pixel records the intensity of the light (A) while the other 3 record the 0º (B), 45º (C) and 90º (D) polarized intensity.

The additional pixel sensitivity to 45º polarized light in sense region 2 is used to compute the Stokes parameters. The procedure to obtain the Stokes parameters with 45º polarized light is not discussed in this paper. The pixels dedicated to sense the intensity in regions 1 and 2 are used to normalize the data obtained from the pixels sensitive to polarization directions.

III. PERFORMANCE ANALYSIS

A. Performance

Linear polarizers are characterized by two main specifications: transmittance and extinction ratio. The transmittance is the fraction of the total incident light that passes through the linear polarizer. The extinction ratio is defined as the ratio of the power of a plane-polarized beam that is transmitted through a polarizer placed in its path with its polarizing axis parallel to the beam's plane, compared with the transmitted power when the polarizer's axis is perpendicular to the beam's plane.

The sensor was illuminated with a polarized light obtained by passing the light from a DC light source through a linear polarizer. The transmission axis of the linear polarizer was then varied from 0º to 180º in steps of 15º to vary the polarization angle of the light reaching the image sensor.

The corresponding analog output of the pixels sensitive to 0º and 90º in the polarization sense region 1 and 0º, 45º and 90º in the polarization sense region 2 are recorded. The obtained analog output is normalized with respect to the intensity obtained at the intensity sensitive pixel, to compensate for any variation in the light intensity and pixel sensitivity over the entire imaging array. The normalized output is the transmittance of the wire grid polarizer. The normalized transmittance as a function of the transmission axis of the linear polarizer (incident polarization angle) for the two polarization sense regions are shown in Figure 5.

The mean maximum (T_{max}) and the minimum transmittance (T_{min}) for 0º and 90º polarization sensitive pixels in the polarization region 1 and 2 are shown in the Table 2.

TABLE 2: Transmittance (%) and extinction ratio (ER)

Region	T_{max}(0º)	T_{min}(0º)	T_{max}(90º)	T_{min}(90º)	ER
1	0.389	0.07	0..444	0.01	6.3
2	0.384	0.0545	0.424	0.06	7.7

The maximum and the minimum transmittance for the 45º sensitive pixel in the polarization sense region 2 are 0.446 and 0.02 respectively, thus the extinction ratio is 22.

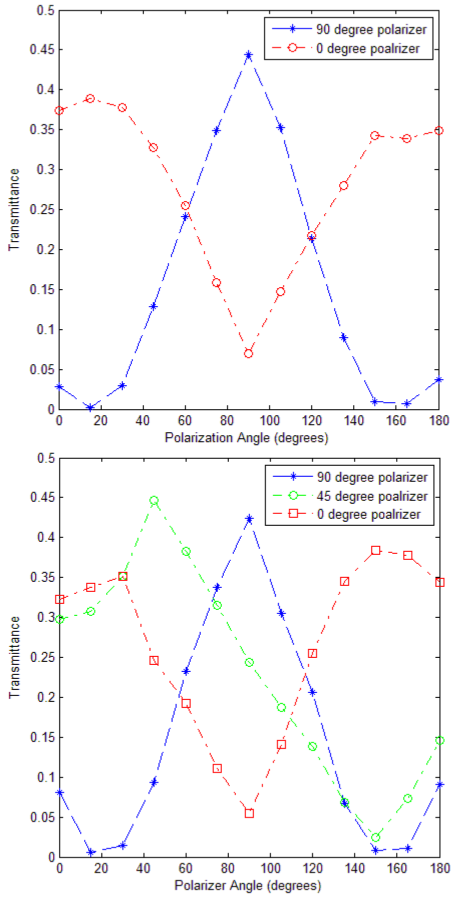

Figure 5: 0º and 90º polarization profile (top) sense region 1, (bottom) sense region 2

B. Material classification using polarization transmittance

Materials are broadly classified into metals and dielectrics based on conductivity. Metals are highly conductive while dielectrics are not. The classification of the material can provide vital information about the scene in computer or machine vision. According to the Fresnel reflection theory [3], dielectric surfaces strongly polarize the light upon specular reflection for all angles of specular incidence when compared to the reflected light from metal surfaces.

When the reflected wave is passed through a linear polarizer, the intensity of the image can be expressed as a function of the transmission axis of the polarizer. The reflected irradiance oscillates between the maximum transmitted intensity I_{MAX} and the minimum transmitted intensity I_{MIN}. The magnitude of oscillation is quite large for dielectrics as compared to metals [3].

The light from the DC source is reflected from the metal and dielectric surface and transmitted through a linear polarizer. Figure 6 shows the measured transmitted irradiance in the sense region 1 and 2 for 0º and 90º sensitive pixels when the reflecting surface selected was aluminum and plastic.

The difference between maximum and the minimum transmitted irradiance for plastic and aluminum surface in the sense region 1 and 2 are shown in table 3.

TABLE 3: Transmitted radiance for plastic and aluminum.

	Region 1		Region 2	
	Plastic	Alum.	Plastic	Alum.
I_{max}-I_{min} (0º)	0.66	0.15	0.466	0.16
I_{max}-I_{min} (90º)	0.67	0.23	0.985	0.10

The transmitted irradiance oscillations range for plastic in sense region 1 is 190% and 340% higher and in sense region 2 is 190% and 885% higher than that of aluminum , for 90º and 0º polarization sensitive pixels respectively. The transmitted irradiance oscillations for plastic at both polarization sense regions 1 and 2 are found to be much higher than those for aluminum. The differences in the transmitted irradiance are due to the difference in the reflection pattern of the light from the aluminum and plastic surfaces. We believe further studies in this area can help to develop a model for real time material classification based on polarization sensing image sensor.

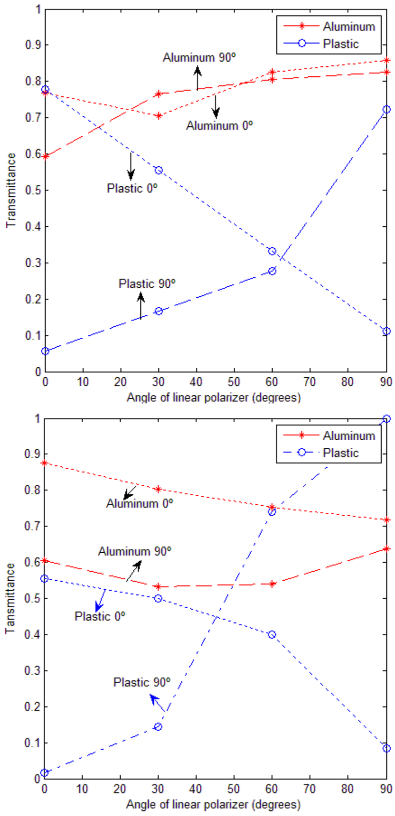

Figure 6: Transmitted Intensity at 0º and 90 º polarization sensitive pixel in sense region 1 (top) and sense region 2 (bottom).

The extinction ratio for the polarization sense region 1 and 2 were calculated to be 6.3 and 7.7 respectively which are higher than the extinction ratio of 2.3 presented by [12], [13] and ~6 at λ=650nm by [14]. A higher extinction ratio of ~ 100 has been reported using organic micropolarizers [6]. The ER has not been reported for the organic polarizers in [9]. For the 45º pixel a higher extinction ratio of 22 is obtained. The absorption of the EM waves to completely S polarize or P polarize the transmitted wave through the wire grid is dependent on the pitch of the wire grid and so the extinction ratio also varies with the pitch. A higher extinction ratio is obtained because of the lower wire grid pitch used in the designed image sensor.

IV. CONCLUSION

A CMOS image sensor using a wire grid to measure polarization information was designed. The different orientation angles of the grid measures the different polarized light intensities. Extinction ratios of 6.3 and 7.7 were achieved in the two sense regions of the sensor. The variation in the transmitted irradiance for aluminum and plastic surface was shown which can be used to model an image sensor for real time material classification.

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