Vertically integrated thin film color sensor arrays for imaging applications

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Abstract: Large area color sensor arrays based on vertically integrated thin-film sensors were realized. The complete color information of each color pixel is detected at the same position of the sensor array without using optical filters. The sensor arrays consist of amorphous silicon thin film color sensors integrated on top of amorphous silicon readout transistors. The spectral sensitivity of the sensors is controlled by the applied bias voltage. The operating principle of the color sensor arrays is described. Furthermore, the image quality and the pixel cross talk of the sensor arrays is analyzed by measurements of the line spread function and the modulation transfer function.

OCIS codes: (040.1240) Arrays; (160.1890) Detector materials; (230.5160) Photodetector;

References and Links

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1. Introduction

Imaging is usually performed by an array of sensor elements in combination with a color filter array (CFA). However, sensor arrays using color filter arrays are limited in terms of their spatial resolution. Three chromatic pixels for red, green and blue are required to generate a color pixel. Furthermore, CFA based sensor arrays exhibit color aliasing effects. To increase the resolution of existing color sensor arrays and to avoid color aliasing effects, vertically

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integrated sensors have been developed. Here the color information is detected in the depth of the sensor.

The operation principle of a color moiré or color aliasing free sensor is schematically illustrated in Fig. 1. An edge was projected on a sensor array using a Bayer filter array and a vertically integrated color sensor array. Due to the finite size of the sensor pixels aliasing effects are observed for both types of sensors. However, for the vertically integrated sensor only black and white aliasing is observed, whereas for the sensor using a color filter array black and white aliasing plus color aliasing is obtained. The influence of the color aliasing effect on the image quality is illustrated in Fig. 1(c) by projecting a black/white edge on the different imagers. The vertically integrated sensor detects the black and white image. The image quality is limited black/white aliasing. The color filter based sensor array detects different colors at the edge even though the image is colorless. This effect is added to the black/white aliasing which is observed for both imagers.

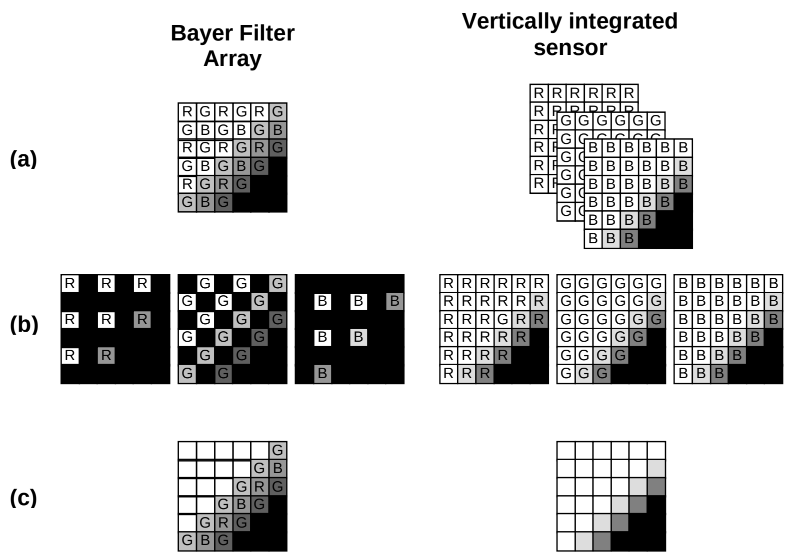

Fig. 1. Schematically illustrated edge detection of a sensor using color filters and a vertically integrated sensor: (a) A black and white image of an edge is projected on the color filter array and the vertically integrated sensor. (b) R, G, and B images of the projected image, (c) Resulting image of the projected edge.

Various vertically integrated sensor structures were proposed and realized to avoid color aliasing effects. Different materials, design concepts and contact configurations were used to realize vertically integrated color sensors [1-6]. The wavelength dependent absorption of the applied semiconductor material leads to the absorption of photons at various depths, so that the color information can be detected in the depth of the device. The suggested sensors range from two terminal devices, which change their spectral sensitivity by varying the applied bias voltage [2-6] to vertically stacked diodes [1].

In this paper we present thin film sensor arrays consisting of vertically integrated amorphous three color sensors in combination with amorphous silicon thin-film readout electronics. The entire sensor array is realized on a glass substrate at low temperatures using a Plasma Enhanced Chemical Vapor Deposition (PECVD) process.

Large area sensor arrays using vertically integrated sensor channels are of interest for a variety of applications. In particular those applications are of interest, where the requirements in terms of cost and scalability are different from classical CCD or CMOS cameras. Typical examples are micro systems like microfluidic microsystems. Here the dimensions are much larger than the feature size of classical microelectronic components and scaling of the individual components is limited.

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After a brief description of the sensor concept of the vertically integrated thin film sensor the fabrication of the sensor array will be described. Afterwards experimental results of the sensor arrays will be presented. In particular, the influence of the device design of the color sensor on the pixel cross talk of the sensor array will be discussed.

2. Experiment

The sensor arrays were fabricated by plasma enhanced chemical vapor deposition (PECVD) at temperatures below 300°C. The sensor arrays have a resolution of 512 x 512 pixels. Pixel addressing is realized by amorphous silicon thin-film transistors (TFTs). Each pixel contains a TFT, a storage capacitor, the color sensor, an address line, and a data line connecting the pixel with the external electronics. A cross section of a sensor pixel is shown in Fig. 2.

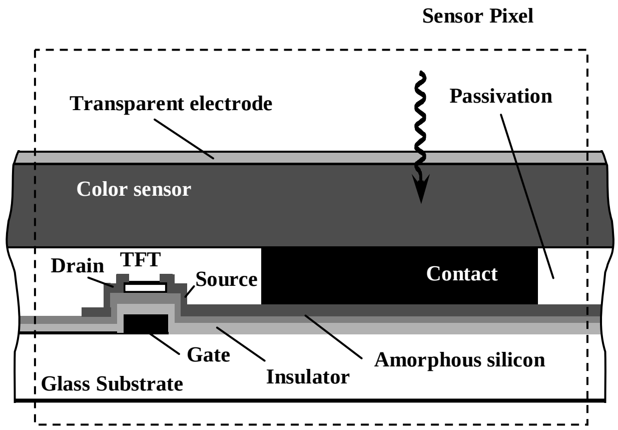

Fig. 2. Cross section of a pixel of a large area color sensor array.

The actual color sensor is realized by an anti serial connection of two amorphous silicon pin diodes, which are integrated on top of the readout electronics. To planarize the readout transistors and to reduce the coupling between the optical sensor and the readout electronics a 3-10µm thick oxynitride layer was prepared on top of the readout transistors before fabricating the sensor stack. Only the back contact and the n-layer of the optical sensor were patterned. The remaining layers of the sensor and the front electrode of the sensor array were unpatterned. The top contact of the sensor array were realized by radio frequency magnetron sputtered ZnO.

Varying the applied bias voltage changes the spectral sensitivity of the sensor. A schematic sketch of the sensor structure consisting of two anti serial connected diodes is shown in Fig. 3.

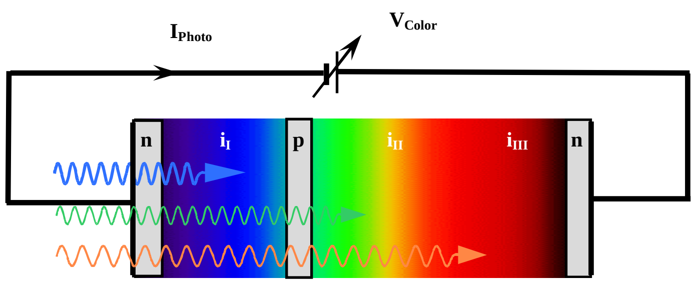

Fig. 3. Schematic cross section of a nipiin color sensor structure

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Applying a positive voltage to the nipin sensor leads to a reverse biased top diode and a forward biased bottom diode. The photogenerated carriers in the top diode determine the photocurrent of the sensor, whereas the photogenerated carriers in the bottom diode recombine. Therefore, the detector yields blue sensitivity. Changing the applied bias towards a negative voltage leads to a forward biased top diode and a reverse biased bottom diode. In this case the sensor is green or green+red sensitive.

For low negative voltages the electric field in the front part of the bottom diode is much higher than the electric field in rear part of the bottom diode, so that the photogenerated carriers in the front part determine the photocurrent. For higher negative voltages the electric field is enhanced throughout the entire bottom diode and the extracted carriers out of the entire bottom diode determine the photocurrent.

3. Results

3.1. Color Sensor

The spectral sensitivity of the sensor array for different bias voltages is shown in Fig. 4. The spectral response was measured by using the read-out electronics of the sensor array. A calibrated crystalline silicon detector was used as a reference to determine the spectral sensitivity of the color sensor.

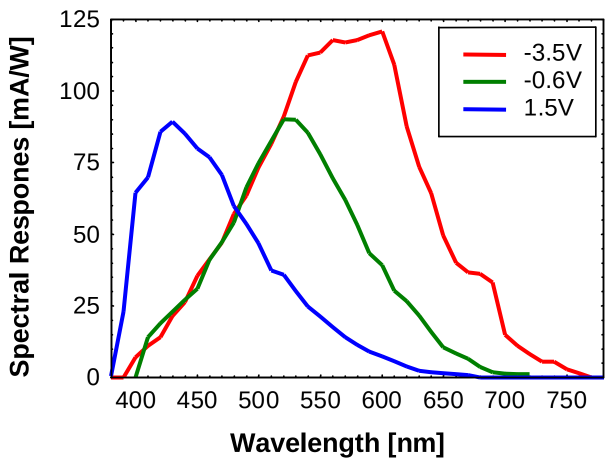

Fig. 4. Spectral response of the nipiin sensors for the applied bias voltages of V=+1.5V, -0.6V, and -3.5V.

The maximum of the voltage controlled spectral response of the nipin structure shifts from red to green and blue due to a change of the bias voltage from V=-3.5V to V=+1.5V. For a bias voltage of +1.5V the sensor exhibits a maximum of the spectral sensitivity at a wavelength of 430nm. Applying a low negative voltage of -0.6V to the optical sensor leads to a shift of the spectral sensitivity. In this case the photogenerated carriers in the front part of the bottom diode determine the photocurrent. The electric field in the rear part of the bottom diode is not high enough to extract the photo-generated carriers out of this region. The sensor exhibits a maximum of the spectral response at wavelengths of 530nm. For higher negative bias almost all carriers can be extracted out of the bottom diode and the maximum of the spectral response shifts to 600nm.

3.2. Sensor Array

A color image taken by the thin-film sensor array is shown in Fig. 5. The image was generated by taken three images for the three colors blue, green, and green+red. The images were taken for a luminous emittance of 100-1000lx. All three images have a resolution of 185 x 280 pixels. The image in Fig. 5(a) was taken for an applied voltage of 1.5V. In this case only carriers generated in the top diode were extracted. For low negative voltages (-0.6V) only the carriers were extracted from region i_{II} (Fig. 3) of the bottom diode leading to the image shown in Fig. 5(b). Accordingly the sensor is green sensitive. For high negative voltages all photogenerated carriers in the bottom diode were extracted, which means that the sensor is green+red sensitive (Fig. 5(c)). Due to a color transformation the images can be separated in red and green images. The color image in Fig. 5(d) is formed by merging the chromatic images.

Fig. 5. Images taken for the applied bias voltages of 1.5 V (a), -0.6 V (b), -3.5 V (c). The images have a resolution of 185 x 280 pixels. A linear color transform was applied to merge the images in Fig. 5(a), 5(b) and 5(c). The RGB image is given in Fig. 5(d).

3.3. Pixel Cross Talk

A comparison of the images taken by the sensor array for the different voltages exhibits a significant difference in contrast for the three monochromatic images. The contrast of the image taken by the top diode of the color sensor array is lower than the contrast of the two other images taken by the bottom diode. The reduced image contrast is caused by pixel cross talk.

To study the influence of pixel cross talk on the image contrast measurements of the Line Spread Function (LSF) were carried out. The Line Spread Function was measured by placing

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a 15 μm slit directly on top of the sensor array. While measuring the Line Spread Function the sensor array was exposed to white light. The normalized Line Spread Function of the bottom diode is shown in Fig. 6. The LSF was measured for different integration times of the sensor array ranging from 50ms to 1000ms. The Line Spread Function is plotted as function of the sensor spacing. A spacing of 0μm corresponds to the center of the main pixel, which was exposed through the slit. The dashed vertical lines in Fig. 6 indicate the pixel pitch of the main pixel. Applying a voltage of -0.6V to the sensor yields green sensitivity. Under such conditions the bottom diode is reverse biased and the top diode is forward biased. For short integration times (50ms) almost no spreading of the photo generated charges is observed. The Line Spread Function is comparable to the Line Spread Functions measured for black/white sensor arrays using amorphous silicon pin diodes [9]. For longer integration times (276ms and 1000ms) the image starts blooming. The pixels get saturated and the photo generated charges start to spread into the neighboring pixels. For long integration times of 1000ms the charges were spread over 4-5 neighboring pixels.

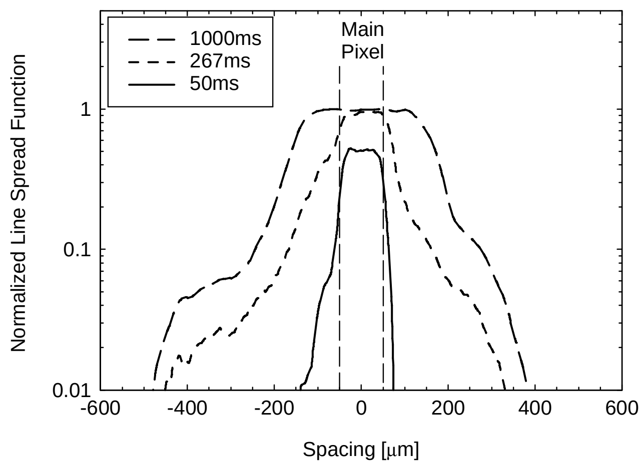

Fig. 6. Measured and normalized Line Spread Function (LSF) of the bottom diode of the color sensor array for different integration times (50ms, 267ms, 1000ms). A voltage of -0.6V was applied to the color sensor.

Another measure of the image quality is the modulation transfer function, MTF. The modulation transfer function is the Fourier transform of the Point Spread Function (PSF), or in 1-dimensional Line Spread Function. In the ideal case the 1-dimensional modulation transfer function can be described as light transmitted through a very narrow aperture, which is sampled by a pixel. In the ideal case the modulation transfer function is described by

$$MTF(f) = \Im(LSF(x)) = \sin c(\pi df) \tag{1}$$

where d is the pixel pitch and f=1/x is the spatial frequency. The MTF has the value unity at spatial frequencies of zero, and decreases to zero at higher frequencies. In the case of an ideal imager the MTF is high for frequencies below the Nyquist frequency, which is given by f_N=1/2d. The modulation transfer function should be low for spatial frequencies above the Nyquist frequency. However, the color sensor array exhibits image spreading so that the measured MTF deviates from the ideal MTF given in equation 1. In order to account for the spreading of the charges in the sensor the modulation transfer function was extended in the following form:

$$MTF(f) = \sin c(\pi df) \cdot \frac{1}{1+\alpha f^2} . \tag{2}$$

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The additional term considers spreading of the charges in the x-direction (perpendicular to the incident light), where α is a spreading coefficient. The measured Modulation Transfer Function of the top and the bottom diode for the different color voltages is shown in Fig. 7 for short integration times (50ms). For the bottom diode the Modulation Transfer Function is very close to the ideal Modulation Transfer Function determined by the pixel pitch (Fig. 7(a)). The measured MTF for the bias voltage of -0.6V only slightly deviates from the ideal MTF (Fig. 7(b)). Increasing the applied bias voltage of the color sensor from -0.6V to -3.5V leads to a slight increase of the charge spreading in the thin film system (Fig. 7(c)).

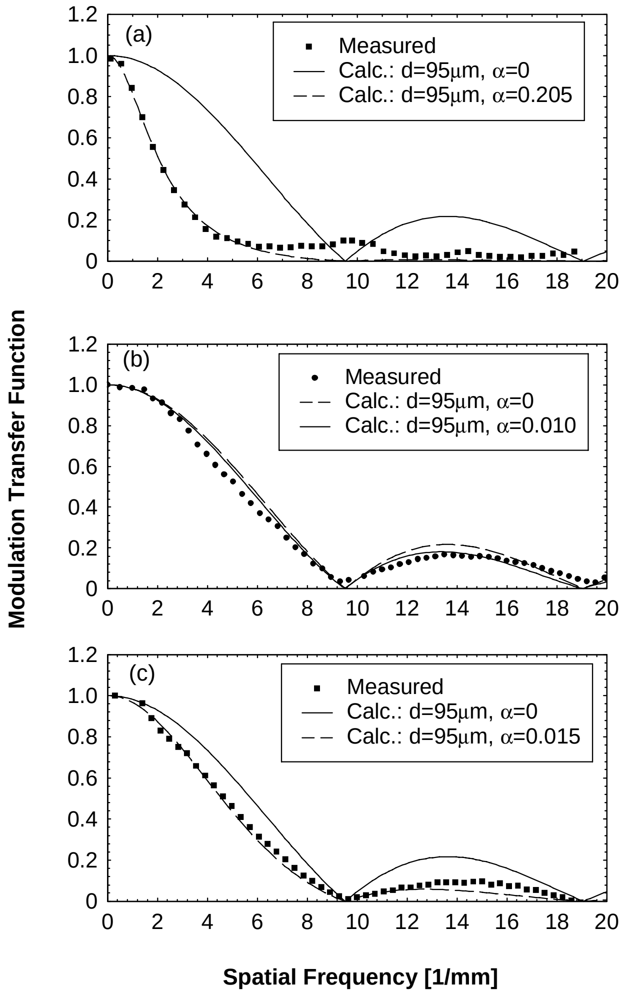

Fig. 7. Measured and calculated Modulation Transfer Functions (MTF) of the top diode and the bottom diode of the color sensor array for applied bias voltages of 1.5V (a), -0.6V (b) and -3.5V (c). The measurements were taken for a short integration time (50ms).

The cross talk behavior of the bottom diode is quite different from the behavior of the top diode. The Modulation Transfer Function of the top diode clearly deviates from the ideal Modulation Transfer Functions. The ideal modulation transfer function and the fit of the measured modulation transfer function are shown in Fig. 7(a). The modulation transfer function can only be described by increasing the spreading coefficient to 0.18. Such behavior is observed independent of the integration times. Even for short integration times the charges start to spread out. This behavior can be attributed to the fact that the entire top diode is unpatterned. The increased pixel cross talk is caused by an electric field gradient along the p-layer of the sensor (Fig. 3). Illuminating the sensor arrays through a very narrow aperture leads to a distinct change of the electrical field distribution in the exposed area of the sensor. The exposure causes a decrease of the built-in voltage for both of the diodes (top and bottom diode) of the color sensor. As a consequence the electric potential in the p-layer of the sensor structure is reduced. Therefore, a spatial variation of the light intensity leads to an electric field gradient along the p-layer, which causes the charges to spread out from the exposed main pixel into the neighboring pixels. Depending on the illumination conditions the electric potential in the p-layer can be changed by up to 150mV. A more detailed description of the device behavior under different illumination intensities is given elsewhere [10]. To reduce the pixel cross talk and to increase the image contrast the p-layer of the anti serial connected diode has to be patterned.

4. Conclusion

A moiré effect or color aliasing free large area color sensor array was characterized in terms of pixel cross talk. The sensor array was fabricated on glass substrates with a resolution of 512 x 512 pixels. The optical sensor and the readout transistors of the sensor array were realized by amorphous silicon and its alloys at deposition temperatures below 300°C. The color detector based on the anti serial connection of two amorphous diodes. Changing the applied bias voltage varies the spectral sensitivity of the sensor. The blue color information is detected by the top diode for positive voltages and green and red sensitivity by the bottom diode for negative voltages. The image quality was analyzed by measuring the normalized Line Spread Function and the Modulation Transfer Function for different voltages and integration times. The image contrast of the blue image is reduced in comparison to the contrast of the red and the green images. The contrast of the blue image - detected by the top diode - is reduced due to a change of the electric potential in the p-layer of the sensor as a consequence of the light exposure. The change of the electric potential leads to a spreading of the charges in the sensor.

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