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Color recognition sensor in standard CMOS technology

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ABSTRACT

Two integrated color detectors are presented as a solution for low cost color sensing applications. The color detection is based on lateral carrier diffusion and wavelength-dependent absorption-depth. The proposed detectors are implemented in a standard 130 nm CMOS technology without process modification or color filters. Three independent output signals are obtained with spectral responsivities optimized to short, middle and long wavelengths. R, G, B or X, Y, Z standard color representation can be realized by a linear transformation of the output signals.

1. Introduction

With the tremendous growth of optoelectronic applications in the field of imaging systems like Active Pixel Sensors (APS) for CMOS cameras during past few years, an efficient method for integrated, low-cost color sensing gets more and more essential. But also general lighting applications like solid-state LED lighting became important demanding integrated low-cost ambient light sensing and color monitoring.

To gain higher flexibility for spectral response optimization, avoiding expensive technology modification like multi-photodiode stacks [1] and external color filters [2], an alternative sensor solution is presented in this paper. Two color sensing structures are proposed consisting of stacked and laterally arranged photodiodes. Color separation between the three photodiodes is achieved by lateral carrier diffusion together with wavelength-dependent absorption.

In Section 2 the used color sensing methods and their theoretical background are presented. In Section 3 the device and process simulations based on Synopsys TCAD tools are discussed. Section 4 shows the proposed sensor structures including spectral light response simulations. In Section 5 the measurement results of both color sensors are reported. Finally the signal processing for realization of a normalized colorimetric output like R, G, B or X, Y, Z is discussed in Section 6.

2. Introduction to color sensing

According to light colorimetric theory, a color measurement requires at least three spectral independent sensor signals with opponent color sensitivity to accurately represent an R, G, B or X, Y, Z color space [3]. Ideally the three signals should be matched to the spectral sensitivity of human eye photoreceptors represented by the color matching functions.

The R, G, B color matching functions describe an appropriate mixing of three defined primary colors that matches a single wavelength color stimulus [4]. The R, G, B color matching functions were defined by experiments and observation according the human eye color perception while the X, Y, Z model was done by a mathematical manipulation of the previous. The Y component of the X, Y, Z model matches the $V(\lambda)$ curve, that represent the luminance of the color. The color matching functions are the standard curves which should be matched by the color sensor responses in order the accurately represent color.

Color sensing in commercial and industrial applications is usually based on Bayer Color Filter Arrays (CFA) [2] or filter-less color sensors [1]. In CFA's a photo sensor with almost constant light sensitivity over a wide spectral range is used, while the color sensitivity is provided by filters added on top of the sensor, as shown in Fig. 1a. An example of a Bayer sensor response is presented in Fig. 1b. Due to the filters, the overall sensor sensitivity is decreased. Furthermore CFA's require complex filter assembly on top of the sensor which significantly increases the production costs.

Alternatively to CFA's, an implementation of filter-less sensor is proposed in the Foveon X3 Technology [1]. This technology is

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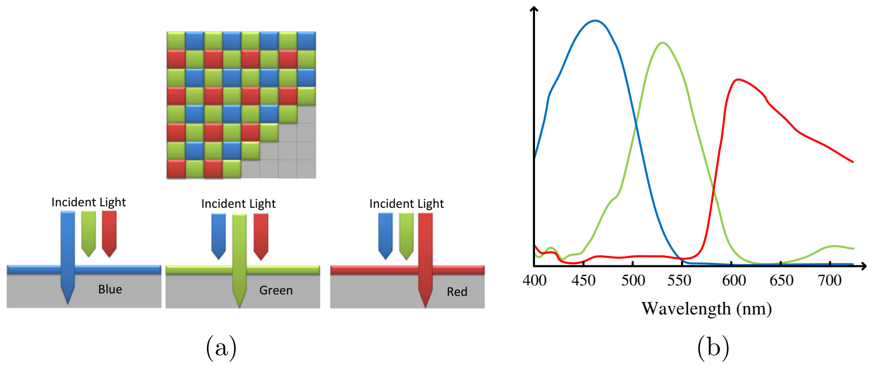

Fig. 1. (a) Bayer color filter array. (b) Responsivity of a CFA sensor [5].

based on the wavelength dependent light absorption properties of silicon and has a stack of three optimized photodiodes, where each absorbs the generated carriers related to different light colors shown in Fig. 2a. The expected response of the three photodiodes is presented in Fig. 2b.

In this color sensor the light intensity can be measured, avoiding absorption losses and it achieves therefore better quantum efficiency compared to sensors with color filters. Even though the triple-junctions are usually available in modern CMOS technologies, the spectral responsivity of the three stacked photodiodes is directly defined by technology parameters like doping concentrations and profiles, and there is almost no room for optimization without expensive technology modifications. Also for older CMOS technologies a triple-well option is not always available.

A main target of the proposed color sensor is using a standard, low-cost CMOS technology, without any process modification. The realization and optimization of the sensor should be done by layout modifications only. In order to avoid filters and technology modifications, the used color detection methods are based on the silicon properties of wavelength dependent light absorption in different depths, together with lateral carrier diffusion effects. These properties of silicon and its application in color detection in standard CMOS technology are explained in Sections 2.1 and 2.2.

2.1. Double photodiode

When light enters the silicon, the photons are absorbed depending on the silicon absorption coefficient α. The absorbed photons generate electron–hole pairs. The number of generated carriers per volume and time is called generation rate *G*. The generation rate exponentially decreases with the silicon depth.

The wavelength dependent light absorption in different depths can be observed on a structure with two vertically stacked photodiodes of a standard CMOS process flow as shown in Fig. 3a [8].

The first pn-junction, PD1, is formed between a shallow p+ implant within the n-well implant. The second pn-junction, PD2, is vertically stacked below the first photodiode, between the n-well and the p-substrate.

Fig. 3b shows the wavelength dependent carrier generation rate. For blue color light, with a wavelengths of about 400–500 nm, the light absorption coefficient of silicon is very high and the carrier generation mainly happens near the silicon surface. Therefore most of the carriers will diffuse or drift to the upper pn-junction PD1, which results in an increase of the PD1 photocurrent. For red light with wavelengths above 600 nm, there is high carrier generation even deep in the silicon, so the carriers are mainly collected by junction PD2 [8].

The two photodiodes, PD1 and PD2, have different spectral responses. PD1 presents a higher sensitivity for low wavelengths while PD2 has very broad response, as shown in Fig. 3c. The current at the terminal PPNW is equal to the current of PD1 while the current at the terminal NW is equal to the currents of PD1 + PD2.

Even though the two diodes have quite different spectral responses, an accurate color measurement requires at least three spectral independent sensor signals to represent an X, Y, Z color space [3]. A third response can be obtained by lateral carrier diffusion as explained in the following section.

2.2. Lateral diffusion

Carrier diffusion happens in regions where no electrical field is present, generally deep in the silicon substrate. The photogenerated carriers in the substrate can diffuse to regions with electrical field, being accelerated within the space charge region contributing to the photocurrent. The diffusion length depends on carrier diffusion coefficient and carriers lifetime and can reach hundreds of micrometers.

The carrier diffusion in a color sensor application is illustrated in Fig. 4a. The structure consists of two n-well/p-substrate

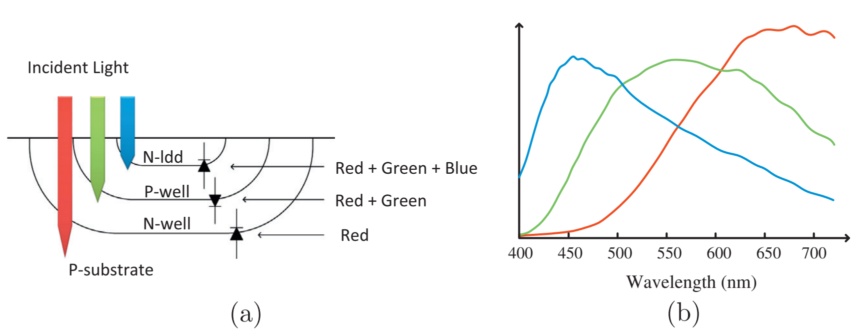

Fig. 2. (a) Stacked-photodiode color sensor [6]. (b) Responsivity of a stacked-photodiode color sensor [7].