A CMOS Image Sensor Employing a Double Junction Photodiode

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Abstract

A CMOS image sensor that employs a vertically integrated double junction photodiode structure is presented. This allows colour imaging with only two, wider bandwidth, filters. The sensor uses a 184 x 154 6-transistor pixel array at a 9.6 μm pitch. Results of the device characterisation, and colour image reconstruction using the prototype sensor, are presented.

1 Introduction

Conventional CMOS colour image sensors employ a standard n+/p diode or photo-gate as the photo-sensing element in an integrating active pixel combined with an array of 3 colour filters, often RBG filters arranged in a Bayer pattern. In a previous paper [1], an alternative pixel structure was described, in which a double junction structure was integrated with active pixel circuitry. Such a sensor has the advantage that a reduced number of colour filters (in this case two) can be used above the pixel array, which results in a more efficient collection of the incident light, and also an equal sampling of all the colour signals in the spatial domain. In this paper, a full CMOS image sensor based on this approach is presented and the colour imaging performance is described.

2 Conceptual operation

The tri-chromatic colour theory states that 3 spectral responses are required for colour reproduction. By using a photo-diode structure with two *p-n* junctions stacked vertically (Fig. 1), two spectral responses are obtained, as short wavelength photons tend to be absorbed nearer the silicon surface than photons of longer wavelength [2]. This results in the spectral responses shown in Figure 2. The responses have been normalised, as they differ considerably in amplitude, but the spectral selectivity is clearly apparent. By combining this structure with two suitable colour filters in a checkerboard array (Fig. 3b), four responses are obtained which is sufficient for colour imaging. In the Bayer pattern (Fig. 3a), twice as many pixels are allocated to green [3]. While this results in improved sampling of the luminance data of the image, it means that colour aliasing is more prevalent in the blue and red channels. With the double junction approach, both pixel types can be used to obtain luminance data (as they are covered with wider bandwith filters), and the colour sampling is equal.

3 Pixel design

In a previous paper, an 8-transistor active pixel was presented which contained both NMOS and PMOS transistors. Such a pixel is very difficult to lay out compactly. Instead, a pixel using only NMOS transistors has been adopted. The pixel circuitry and layout are shown in Figures 4-5. The pixel consists of six transistors, 2 for read select (M2 & M5), two source followers (M3 & M6), and two for reset (M1 & M4). The pixel is operated in a reset-integrate-read sequence: the two photo-juctions are reset to *Vrtn* and *Vrtp*, then allowed to integrate the photocurrents, after which the read transisors are enabled and the voltages *VoutN* and *VoutP* read out. Standard correllated double sampling is used to remove offsets due to the pixel source followers.

The pixel has a pitch of 9.6 μm in a 0.35 μm technology with a fill-factor of 19%. For comparison, a standard 3T pixel implemented in the same technology can achieve a fill factor of 27% at 6.2 μm pitch. Smaller pixels are possible, but the fill-factor begins to dramatically reduce due to the well spacing rules. With microlenses the optical fill-factor can be improved considerably.

4 Prototype sensor

To test the performance of the pixel in an imaging application, a simple 184 x 154 (QCIF resolution) array with purely analogue readout was implemented. A die micro-graph is shown in Figure 6. Metal 3 was used as a light shield in the pixel array to ensure that incident light was absorbed vertically by travelling through both junctions. This was required to maximise the spectral selectivity of the junctions. Analogue-to-digital conversion and line timing generation were implemented off-chip. The colour image reconstruction process, including column fixed-pattern-noise removal, was implemented in software and is discussed in section 5.

Table 1 summarises the performance of the prototype sensor. Despite the good microlens fill-factor, the sensitivity of the device is quite low. This is partly due to the low conversion gain in the pixel (a result of the pixel capacitance) but also that the microlens has not been optimised for this pixel size. A further problem with the present sensor is that a large gain non-uniformity is observed for the P+/N-well photodiode. This requires correction during the image reconstruction process. However, the dynamic range, saturation SNR, and dark current are all of an acceptable level.

Parameter	$n_{well}/p_{substrate}$ **output**	p^+/n_{well} **output**
Technology	0.35 µm single poly triple metal	
Resolution	184 x 154	
Pixel size	9.6 µm	
Microlens fill-factor	77 %	
Sensitivity (mono)	250 mV/ lux.s	182 mV/ lux.s
Conversion gain	13 µV/e^-	9 µV/e
Conversion gain non-uniformity	< 1%	8%
Dark current @ 25^{o}C	190 pAcm^{-2}	95 pAcm^{-2}
Maximum cross-talk	3%	1%
Random noise floor	73 e^-	88 e^-
Dynamic range	56 dB	46 dB
Saturation SNR	47 dB	43 dB

Table 1: Sensor performance

5 Colour image reconstruction

The colour image reconstruction for the sensor has been implemented in software. A block diagram of the reconstruction process is shown in Figure 7. As a suitable colour filter process for the sensor was not available, a checkerboard array of cyan and yellow filters was simulated by subsampling and combining two images taken with different filters placed in front of the camera. The reconstruction process is fairly simple:

- Before further processing the fixed pattern noise is subtracted using a reference frame and P+/N-well gain non-uniformity was corrected using a gain map.
- Bilinear interpolation is used to estimate the missing pixel data for the four spectral responses. As all the spectral responses are sampled at the same frequency, this algorithm is fairly well suited to the data.
- The interpolated data is then passed through a 3x4 colour correction matrix and white balance gains are applied to obtain RGB data for each pixel.
- In parallel with the interpolation and matrixing process, a high pass filtered version of the luminance data is generated using a Laplacian filter. Every pixel of the array can be used for this process, as the colour filter array contains colours of wide enough bandwidth that every pixel can be used to estimate the luminance. This high pass filtered data is then added to the RGB values to perform apperture correction (also known as peaking) [4], resulting in the final image.

An example image obtained from the sensor can be seen in Figure 8.

6 Colorimetric accuracy

The colour matrix for the sensor was fitted using the 24 colours of the Macbeth colour chart. The colorimetric accuracy of the system can be examined by plotting the errors after matrixing in the *u'v'* plane, where equal distances appear as approximately equal changes in colour to the average human observer [4]. Such a plot is shown in Figure 9 for a cyan and yellow filter combination. Other filter combinations were investigated, but cyan and yellow was found to result in the best trade-off between accuracy and the noise added by the matrixing process to the image.

Compared with the errors for an RGB sensor implemented in the same technology (Fig. 10) the new sensor's performance is considerably worse. To improve the colour reproduction, it seems likely the the spectral response of both the filters and the photodiodes needs to be optimised. The cyan and yellow filters used were simply standard filters intended for photographic purposes and are not optimised for the application. On the other hand, the RGB sensor used the commercial RGB filter process, which has been optimised for the application. Regarding the raw photodiode performance, device simulations show that junction responses can be significantly altered by changing the doping profiles. However, such an optimisation would require a non-standard manufacturing process with custom photodiode implant steps, which would increase the process cost.

7 Colour aliasing

The colour aliasing properties of the sensor have been examined using a 2-D chirp (a linearly increasing frequency modulated tone) as the test pattern. Figure 11 shows the reconstructed image from the double junction sensor, while the output from a Bayer patterned sensor is shown in Figure 12. Note that the Bayer sensor is CIF resolution which the new sensor is only QCIF, which explains why the Bayer image exhibits less visible interpolation artifacts.

With the Bayer pattern, the aliasing manifests itself as blue and orange in the vertical or horizontal directions, while in the 45^{o} direction as magenta and green. With the new sensor, a different aliasing artifact is present which appears as cyan, yellow, and magenta moiré patterns. It occurs first in the 45^{o} direction where the spatial sampling rate is lowest.

8 Conclusion

A new CMOS image sensor which uses a double junction pixel structure to combine the spectral selectivity of silicon with a suitable colour filter combination has been presented. Currently, the colour reproduction of the sensor is not as good as the more usual RGB approach, and further optimisation is required. However, it has been shown that colour reproduction is possible with a reduced colour filter set, and that the sensor colour aliasing artifacts are reduced as expected when using simple reconstruction algorithms. Further work is required to improve the pixel sensitivity and spectral responses to make the technique competitive with commercial sensors.

9 Acknowledgements

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References

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[3] B.E. Bayer, “Color imaging array”, US Patent 3971065, Mar 1975

[4] R.W.G. Hunt, *The Reproduction of Colour,* Fountain Press, 5th Edition, 1995

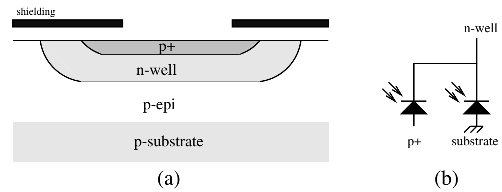

Figure 1: Double junction structure (a) and equivalent circuit (b)

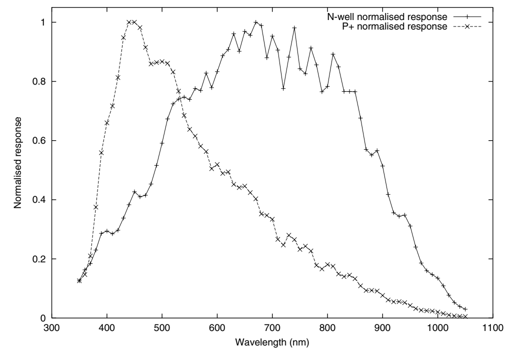

Figure 2: Spectral response of the double junction photodiode

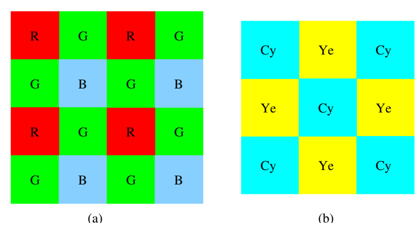

Figure 3: Bayer and double junction filter patterns

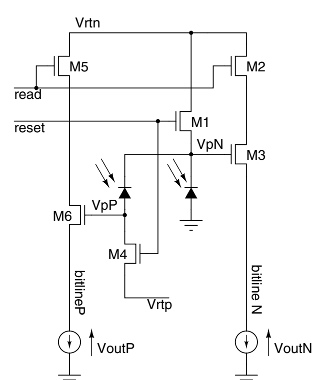

Figure 4: Active pixel circuit.

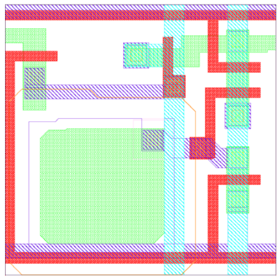

Figure 5: Active pixel layout

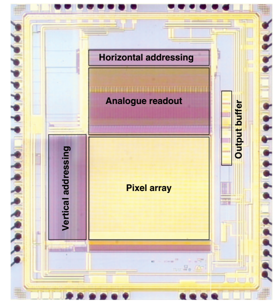

Figure 6: Sensor die micrograph

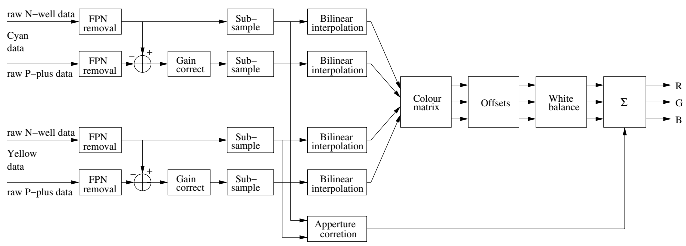

Figure 7: Block diagram of colour reconstruction process

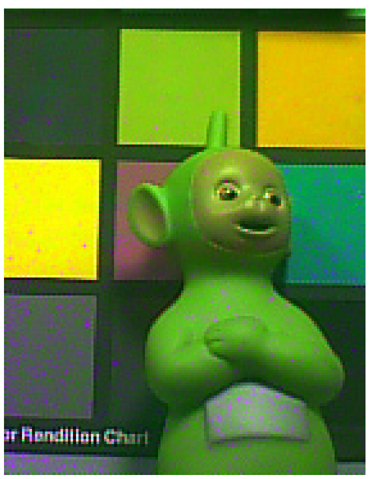

Figure 8: Example image from the sensor

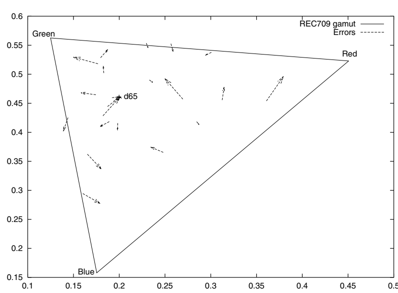

Figure 9: Error vectors after colour matrixing

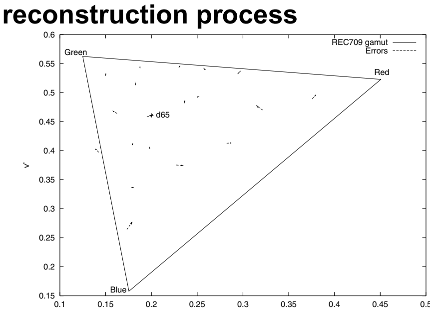

Figure 10: Errors for a RGB sensor.

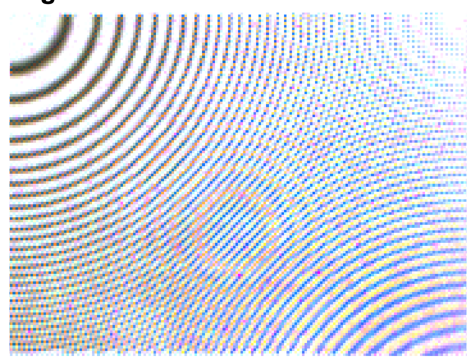

Figure 11: Alias patterns of the new sensor

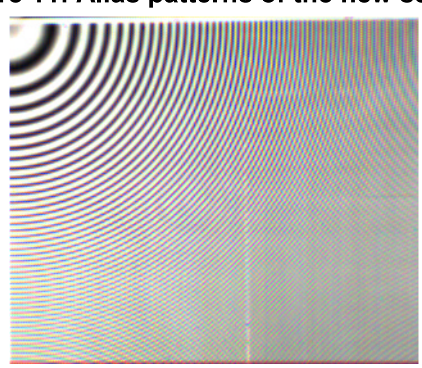

Figure 12: Alias patterns of a Bayer sensor