A 640x480 CMOS Image Sensor for High Speed Image Capture

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Abstract

This article describes a CMOS image sensor designed for high speed inspection applications. The sensor has 16 analog outputs, which can each operate at a 50 MHz data rate and allow for image capture at 1600 frames per second. The image sensor has exposure control functionality, antiblooming capability and a non-rolling shutter architecture to implement snap-shot image capture mode. The pixel architecture incorporates 5 transistors on a 15.3 micron pitch with 50% fill factor.

I. Introduction

To date, most CMOS image sensor development has been directed at relatively slow speed image capture. Increasingly CMOS image sensors are being used for high speed, high resolution applications that until recently were the exclusive domain of CCD imagers.[3-6] In this paper we describe a 640 x 480 CMOS image sensor that eliminates the image lag and rolling shutter artifacts that have hitherto prevented the application of CMOS imagers to high speed image capture.

We have fabricated both monochrome and colour versions of the sensor. The colour sensor has a Bayer pattern array of Red, Green and Blue filters deposited on chip.

II. Sensor design

The main functional blocks of the sensor are illustrated in
Figure 1. The image array has a 15.3 micron square pitch and achieves 50% fill factor with a five transistor pixel circuit. A series of multiplexers is used to transfer signals from all column amplifiers through to 16 analog outputs. The last stage multiplexer can be configured by the user so that the frame data is routed through 1, 2, 4, 8 or 16 analog outputs thus allowing the sensor to satisfy a wide range of frame rate requirements and output data formats. The maximum frame rate when all 16 outputs are operated in parallel is 1600 fps. The maximum frame rate through a single output is 150 fps.

The pixel readout technique produces an analog signal that is difference sampled with respect to the pixel reset level. Each column amplifier is configured to eliminate amplifier offset, which is one component of fixed pattern noise. To enable 50 MHz data rates, pipeline delay circuitry is used for the first two multiplexer stages. A 4:1 mux at the second stage allows the amplifier array to work at the maximum data rate.

A schematic diagram of the pixel circuit is shown in Figure 2. Five transistors are employed in each pixel to implement frame capture, exposure control, a source follower amplifier, pixel reset, and row select. During frame exposure photoelectrons are collected in the photosite diode located between the PR and TCK gates. After frame exposure the TCK gate is globally clocked to transfer charge to the light-shielded storage/sense node located between the TCK and RST gates. The storage/sense node voltages are subsequently read out in a line by line fashion. The photosite and the storage/sense nodes are “hard” reset to eliminate image lag. The PR gate is also clocked globally and allows for anti-blooming and exposure control.

Exposure control is an important feature because it enables a mode of operation with low lag. Lag signal is proportional to kTC/e, where C is the capacitance of the photosite, T is temperature, k is Boltzmann’s constant, and e is electron charge. However, the capacitance of the sense node is considerably smaller than that of the photosite to obtain high responsivity (for a given pixel size). Therefore lag can be quite significant in a frame capture CMOS device if measures are not taken to remove it. In high speed applications, long transfer times cannot usually be accommodated. In this sensor, the approach used to reduce lag is to inject a signal charge from the VPR node. This is accomplished by turning the PR gate on to a potential higher than VPR plus the threshold voltage, while VPR is held at a dc voltage. The amount of signal injected is determined by the dc bias on VPR. The lag signal is eliminated because the dark offset level is reset on each frame. Therefore inefficient transfer of signal out of the photosite does not affect the dark offset level of a pixel for the next frame. The PR gate also allows for antiblooming, a functionality that would normally be implemented in a conventional CMOS image sensor through the RST gate.

III. Test results

3.1 Saturation signal

Sensor saturation level has been defined by linearity of photo-response. Sensor output signal was measured as a function of input illumination power. Typical results are shown in Figure 3. A linear regression analysis was performed to determine the deviation of measured signal from a linear response. The number of data points used for the linear regression was restricted to five, to ignore the two extreme points. Saturation level is determined by a deviation from linear behavior of more than 5% of value predicted by linear regression. In the case shown in Figure 3 the highest illumination level did not exceed saturation, but for some devices a saturation level of 1200 mV was measured by this technique.

3.2 Responsivity

Spectral responsivity curves were measured for both monochrome and colour devices with 10 nm bandwidth. The results are shown in Figure 4 and Figure 5.

3.3 Lag

Lag measurements were made for two operating modes: exposure control off (dc PR bias) and on (clocked PR bias). The first field lag signal with exposure control off was measured to be 100 mV at 800 mV signal level. With exposure control on the lag signal was below the measurement limit of our technique, which was estimated to be 20 mV.

3.4 Pixel to storage node cross talk

Ideally the sense node would not be photosensitive. However, due to imperfect lightshielding and less than perfect collection efficiency by the photosite, some photogenerated electrons can be collected directly in the sense node (e.g. electrons generated deep in the substrate and that migrate to the sense node). This crosstalk was measured to be 1.5% by comparing signal levels for normal readout mode and readout with dc TCK voltage. Crosstalk can affect sensor performance in two basic manners. The first effect is that the signal level in exposure control mode is a function of frame rate as well as exposure time. The second effect is that a rolling shutter artifact can be introduced into the image. The rolling shutter artifact appears because crosstalk signal collects in a particular sense node between pixel reset events, which occur at different times for each row in the array. At very short exposure times and for constant illumination, the output signal will not approach zero as the exposure time approaches zero.

3.5 Random noise

A photon transfer curve is shown in Figure 6. Two identical frames were subtracted and the noise was calculated as $1/\sqrt{2}$ of the rms noise of a full frame. At high signal levels the noise increases as the square root of signal (slope of graph is 0.51), which indicates the noise is dominated by the shot noise of the signal. The intercept of this graph indicates the conversion gain is 8 e/DN. The noise floor is approximately 40 electrons, which indicates the dynamic range is 1140:1 (61 dB).

3.6 Antiblooming

A lens was used to focus light to a small spot in the array. The spot size was approximately 22 pixels in diameter (0.16% of array area). Spot profiles are shown in Figure 7. The width of the spot was measured as the width above 200 DN. The illumination power was increased from near saturation exposure to approximately 220 times saturation exposure (with a fixed exposure time). The increase in width of the spot is shown in Figure 8. Note that some increase in spot width is expected due to increased illumination in the wings of the spot. An estimate of the expected increase due to this effect is difficult to make because the profile of the spot was not measured with sufficient accuracy. The signature of blooming behaviour is a rapid increase in spot width as a function of illumination power. This signature was not observed up to 220x saturation exposure.

3.7 Fixed Pattern Noise (FPN) and Non-Uniformity of Photoresponse (PRNU)

Due to the charge injection technique used in exposure control mode, pixel-to-pixel FPN and PRNU are 8.3 and 1.8 times respectively larger than the results without exposure control. We have characterized the non-uniformities in both normal mode and exposure control mode. For exposure control mode an injected charge level of 200 mV was used. FPN and PRNU without exposure control and some other sensor parameters are listed in table 1.

Conclusions:

We have presented some design details and characterization results for a 640 x 480 CMOS image sensor designed for high speed imaging applications.

ACKNOWLEDGMENTS

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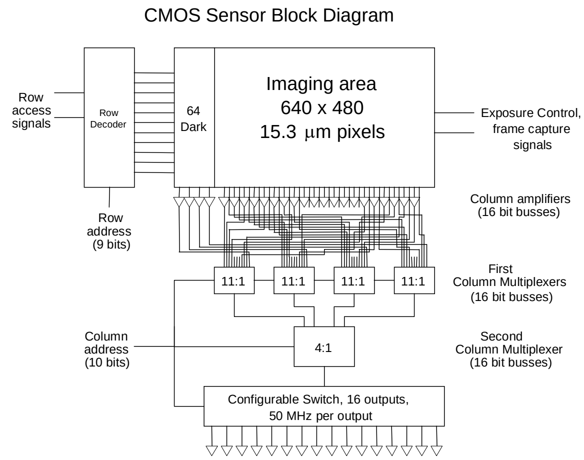

Figure 1. Block diagram of image sensor.

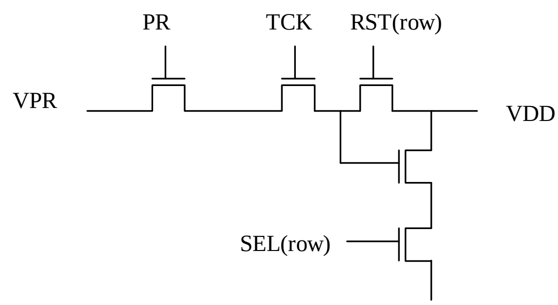

Figure 2. Schematic diagram of pixel circuit.

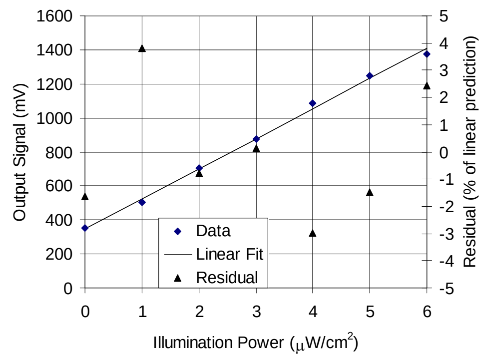

Figure 3. Photoresponse of image sensor. Absolute signal plotted against left axis, and deviation from linear behaviour plotted against right axis.

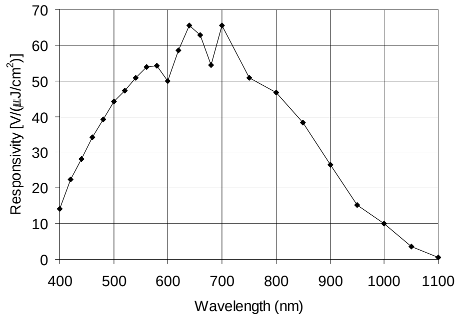

Figure 4. Responsivity of monochrome sensor measured with 10 nm bandwidth.

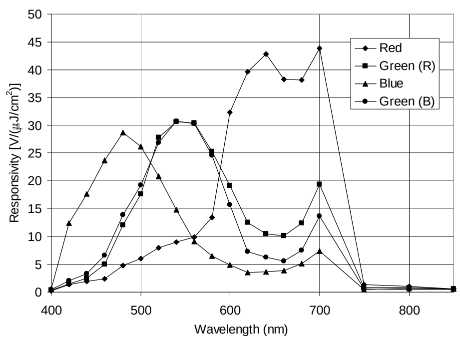

Figure 5. Responsivity of colour device measured with 10 nm bandwidth. Colour of a pixel is separated into Blue, Red, Green adjacent to Red, Green adjacent to Blue (as in the Bayer pattern).

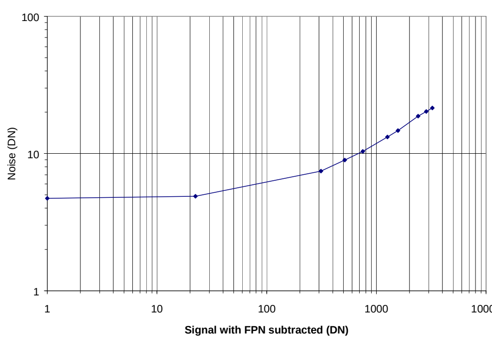

Figure 6. Photon transfer curve. The data was obtained with 12 bit digitization in single output mode at 50 MHz data rate. Conversion gain was set to 0.21 mV/DN.

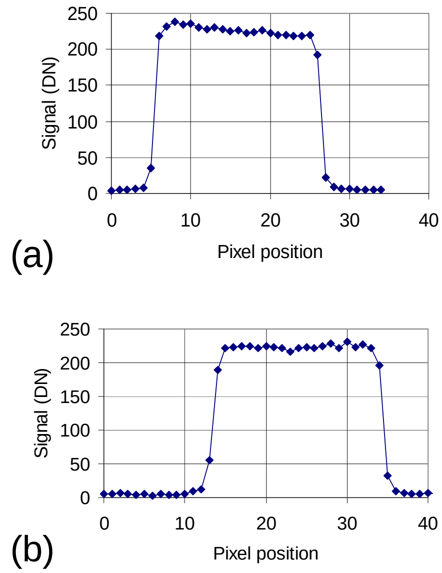

Figure 7. Profile of spot used to measure antiblooming performance (a) vertical dimension, (b) horizontal dimension.

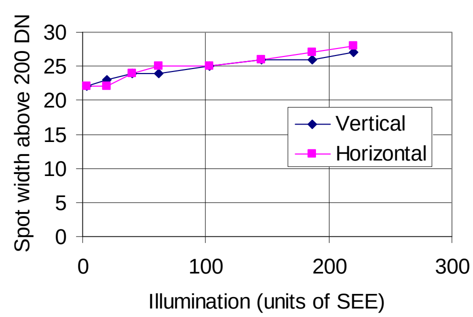

Figure 8. Increase in spot width as function of illumination in units of saturation exposure (SEE).

Table 1 – Sensor Performance Results.

Parameter	Test Result
Saturation Level	1.2 V
Responsivity	60 V/μJ/cm^2
Dynamic Range	61 dB
PRNU	4%
FPN	4%
Channel-to-Channel Nonuniformity	6%
Image Lag	<2%
Antiblooming	220x