A 4M, 1.4e- noise, 96dB dynamic range, back-side illuminated CMOS image sensor

Xinyang Wang, Cheng Ma, Yang Liu, Yang Li, Quan Zhou

[1] Gpixel Inc., ChangChun, China

Xinyang.Wang@gpixelinc.com, +86 – 431 - 86176685

Abstract

In this paper, we present the design, manufacture and characterization results of a 4M, 2048 x 2048 resolution, high dynamic range, low noise CMOS image sensor. The front-side illuminated sensor, GSENSE400, had been successfully characterized and commercialized. The details of the sensor design and measurement results is published in [1]. This paper addresses the further improvement of GSENSE400 sensor, mainly in the follow two aspects: the dark current reduction with cooling, and its backside illuminated development for enhanced UV and visible range sensitivity.

Introduction

For bio-imaging, astronomy, star-tracking applications, a low noise, low dark current and high dynamic range image sensor is desired. For decades, CCD sensors had dominated these applications for its very low dark current and good sensitivity. In 2011, the first scientific CMOS (sCMOS) image sensor was announced by Fairchild imaging, benefits from the very low read noise and high dynamic range, the sCMOS sensor quickly out-performs many CCD sensors, especially when the exposure time is short than a few hundreds seconds.

In this paper, we present a scientific CMOS image sensor using a rather big pixel size to maximum its sensitivity. Based on standard 4T pixel, one additional transistor is used in the pixel to change the pixel conversion gain during readout in order to achieve HDR. The pixel noise is optimized through a low-noise source follower and readout chain. Special attention had been taken during the sensor design to achieve a dark current as low as possible, especially in cooling condition. The sensor was designed with back-side illumination compatible, and by using different ARC architecture, two different types of BSI versions has been fabricated and fully characterized. Because of its superior sensitivity, noise, dynamic range and QE in UV and visible range, this sensor, GSENSE400 & GSENSE400BSI had been proven to be a very suitable candidate for bio-imaging, astronomy and other applications where extremely low light condition is required.

Sensor design and characterization result

The pixel design is based on a 4-T PPD structure which can incorporate CDS for KTC noise and offset cancelling, as shown in

Figure 1(a), one HDR transistor is used for DR enhancement. This simplifies the pixel routing and higher fill factor can be achieved. Figure 1(b) illustrates the pixel operation timing and the bus voltage during the readout of one line. Figure2 shows the full chip architecture. The pixel array is 2048 x 2048 with 11 um pitch. The image signals from the pixel array are sent to the column-level PGA for amplification first, and then feed into a low-power ADC array for digitization. The digitized image signal are then multiplexed and read out through 8 LVDS outputs placed at the bottom of the chip. Figure 3 shows the FSI sensor and a Chinese Yuan coin. In addition, a new column-level ramp ADC has been used in this sensor, comparing to conventional architecture, the new ADC consumes much less power and shows better ground or supply noise rejection. The details of the sensor design can be found in [1].

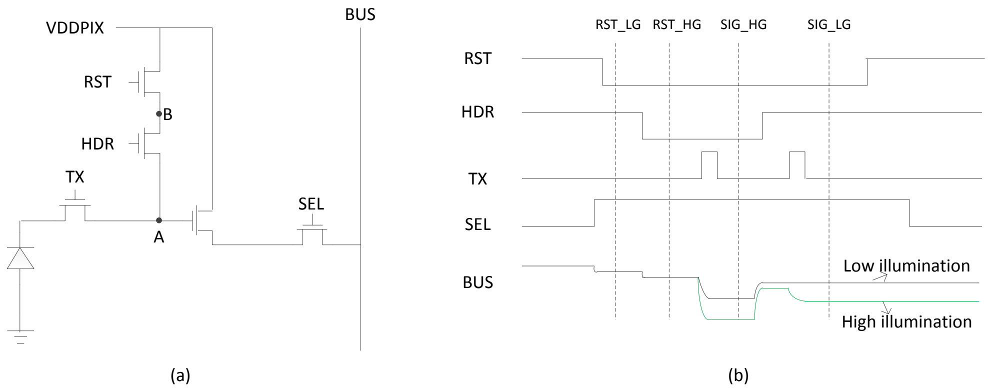

Figure 1 Pixel schematic (a) and operation timing (b) used in the design

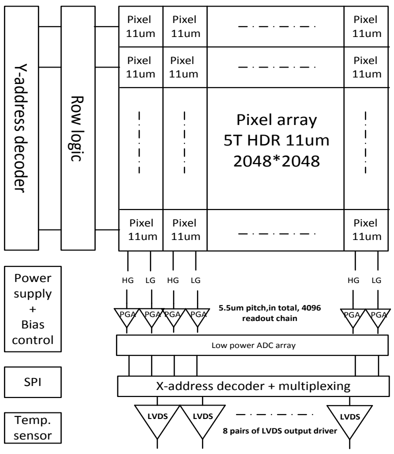

Figure 2 Chip architecture

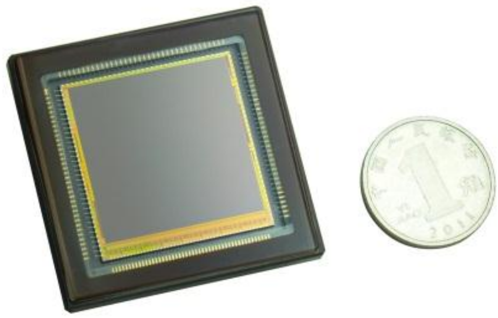

Figure 3: GSENSE400 and a coin of one Chinese Yuan

Sensor characterization results

Benefiting from the specific pixel design and readout method, the designed sensor achieves a dynamic range of larger than 96dB, a readout noise of less than 1.47e-. Table 1 summarized part of the sensor specifications.

Table 1 Sensor specifications

Pixel resolution	2048 x 2048
Pixel pitch(um)	11
Fill factor	74%
Full well(e-)	120k
Dark noise(e-)	1.47
FPN	<0.1%
Frame rate(fps)	HDR:24 / STD:48
Dark current(e-/s/pix)	0.15 @-20^{o}C

Dark current reduction

For scientific image sensors, the dark current behavior is very important as the sensor may be used with very long exposure time. The FSI GENSE400 sensor has a quite low dark current in room temperature, around 30e-/p/s. in theory, the sensor dark current should reduce by half every 6 -10°C when the sensor is cooling down, however, it was not the case as shown in Figure 4 (a). As can be seen, the dark current seems stuck around 20e-/p/s even the sensor has been cooled down to -30°C. During this measurement, the pixel FD node is always in reset mode, i.e. being short to VDDPIX to avoid blooming. As an experiment, the FD node was left floating during exposure, and the sensor dark current result was shown in Figure 4 (b). As can be seen clearly, the pixel dark current is decreasing further if the FD is left floating during exposure. Such behavior indicates that the sensor dark current was dominated by the dark current generated from the TX region. Reducing the electrical field from the PPD to FD helps significantly to reduce the pixel dark current.

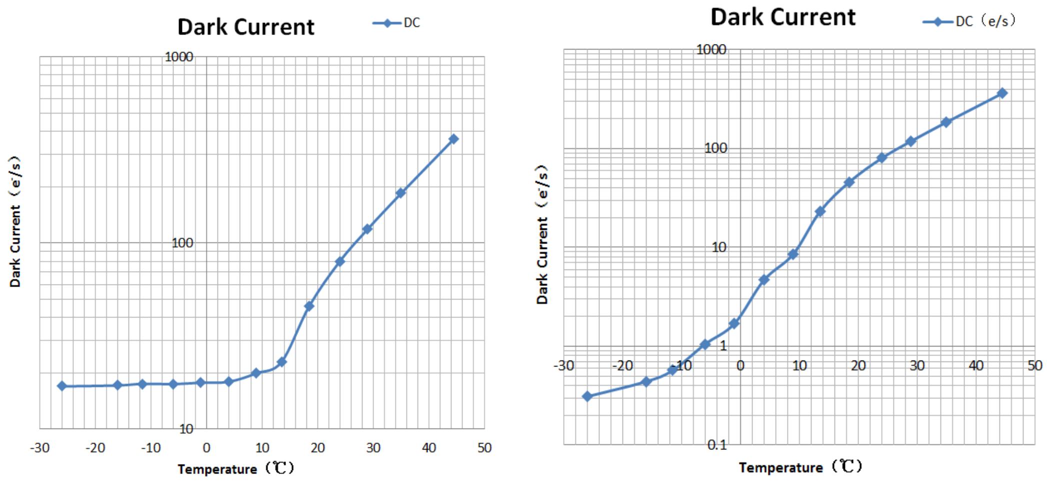

Figure 4: Dark current measurement: (a) – FD in reset mode during exposure; (b) – FD in floating mode during exposure.

When the sensor is cooled down to below -30°C degree and its exposure time is extended to a few hundred of seconds, other abnormal behaviors showed up because the image is now very sensitive to even a slightly non-uniform heat dissipation. Figure 5 shows two bright spots in the image at -20°C, which is due to a high frequency clock pads, and a high power consumption buffer. Both spots had to been removed through alternative timing, or external provided sensor biasing.

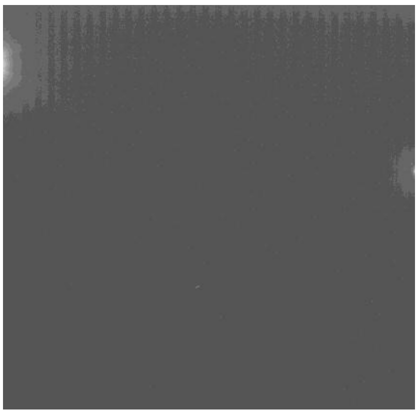

Figure 4 – dark image taken at -20°C

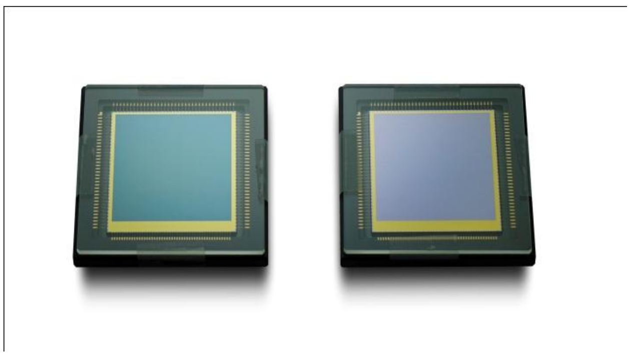

Figure 5 – GSENSEBSI sensor image

- **Back side illuminated GSENSE400**

To further increases the sensor sensitivity, in particular in the range between 270 – 400nm, two different version of BSI GSENSE400 was developed, as shown in Figure 6. Different ARC scheme was applied to the back side of the sensor to optimize its transmission in the visible light range or the UV range. Both coating uses a combination of silicon oxide and silicon nitride layers to ensure a good reliability and process compatibility.

Figure 6 shows the measured QE of both BSI sensors and the FSI sensors from 250nm – 1000nm wavelength. The red curve, of which the sensor is optimized for visible light, reaches its peak QE of 90% around 400nm, while the blue curve, which is optimized in UV sensitivity reaches peak QE of 80-85% around 270nm.

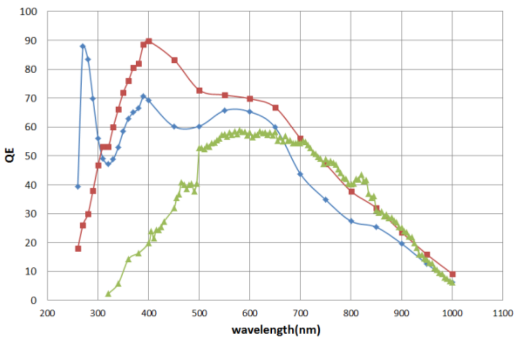

Figure 6 – QE of GSENSE BSI sensor

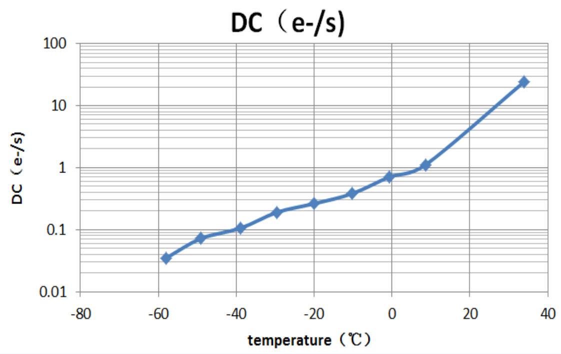

Figure 7 – dark current of GSENSE BSI sensor

Figure 7 shows the dark current measurement of the visible range optimized BSI sensor. As can be seen, although the sensor dark current is higher than the FSI sensor in room temperature, it reduces significantly with cooling. Actually reach the same level as the FSI sensor already around 0^oC. Once being cooled down to -60^oC, its dark current is as low as 0.025e-/p/s.

Figure 8 shows a fingerprint image taken by the GSENSE400BSI sensor with 185ms exposure time under a 254nm UV light with F4.5 lens.

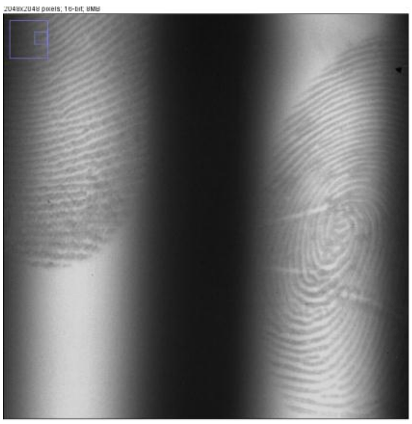

Figure8 – Fingerprint under 254nm UV light with GENSE400BSI

Conclusion & Acknowledge

In conclusion, a scientific CMOS image sensor has been design and manufactured with both FSI and BSI versions. It reaches a noise level as low as 1.2e- (BSI), linear FWC of 90Ke- and peak QE of 90%. When cooled down to -60^oC, its dark current reduces to 0.025e-/p/s. These features make the sensor perfect to be used in bio-imaging, astronomy, spectrometer and other scientific applications. The author likes to thank the CIS R&D team from Towerjazz to support the sensor manufacture, and in particular during the joint development of the BSI version.

Reference

[1] – "A 4MP high-dynamic–range, low-noise CMOS image sensor", Cheng Ma et al., SPIE electronic imaging, San Francisco, US, Feb 2015