# A 35 mm 13.89 Million Pixel CMOS Active Pixel Image Sensor

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## Abstract

This paper discusses a 13.89 million pixels CMOS image sensor for digital SLR cameras. The pitch of the 3-transistor active pixel is 8 microns. The sensor has a full well charge of 117K electrons and 33 electrons temporal noise, and a dynamic range of 71 dB. The fixed pattern noise is 0.14% RMS, obtained by an on-chip correction circuit. Color filters have been optimized for best photographic performance. The pixel array area is equal to the size of 35 mm film (36 x 24 $mm^2$). Essentially, this means that the photographer gets the same image with the digital camera as with film, without lens magnification factor. Two technological challenges have to be overcome to make a sensor of this size. The sensor size exceeds the field area of steppers used to fabricate sub-micron CMOS chips. To solve this, a stitching technique has to be applied during processing of this device. A second problem of such large devices is the variation of the angle-of-incidence of the light on the silicon, causing the efficiency of microlenses to vary along the focal plane. To avoid this problem, a pixel design with an inherently high fill factor is used. The product of fill fact or and quantum efficiency on this pixel is 30%, a number that can not be further increased by the use of microlenses.

## 1. Introduction

Professional digital SLR camera's are present on the market for a few years now. Most make use of charge-coupled devices for image capture, but recently also CMOS image sensors did find their way to this type of products.[1] Up till recently, the size of the image sensors used in this type of product is smaller than the size of the film negative. Consequently, the photographer had to multiply the lens focal number by the area difference between the sensor and the standard 35 mm film negative (for which the lens was designed). Wide-angle photography was only possible with very wide angle lenses. Furthermore, not the same depth of field was obtainable since this depends on the absolute area of the image capture device.

To overcome these limitations a sensor with the format of negative of film has to be developed. Several sensors have been made in the past with this format.[2-4] The sensor presented here offers the highest resolution available in this format at this moment.

## 2. Size of the Pixel Array

The required size of the pixel array is equal to the size of a 35 mm film negative, namely 24 x 36 $mm^2$. Including peripherical circuits, the chip measures 26 x 38 $mm^2$. This size is well beyond the size of reticles used in today's lithographic equipment. But by its nature, the design is largely repetitive. Parts of the reticle are projected repetitively next to each other. In this way the imager is 'stitched' together. Figure 1 shows this configuration. The repetitive block 'E' contains all the pixels. It is 1512 x 1512 pixels large. The focal plane is formed by 3x2 of such repetitive blocks, resulting in a resolution of 4536 x 3048 pixels. The side blocks F and B contain extra pixels intended for black reference. There are 2 horizontal and 1 vertical stitch boundary line going through the focal plane. The other boundary lines are at the egde of the pixel array.

| A | B | B | C |
|---|---|---|---|
| D | E | E | F |
| D | E | E | F |
| D | E | E | F |
| G | H | H | I |

*Figure 1. Composure of the chip from reticle exposures*

## 3. Pixel

The pixel is implemented as a classic 3-transistor active pixel[5] (figure 2). The pitch is 8 microns. In order to achieve acceptable yield performance, care is taken of all the critical interconnections passing through the pixels.

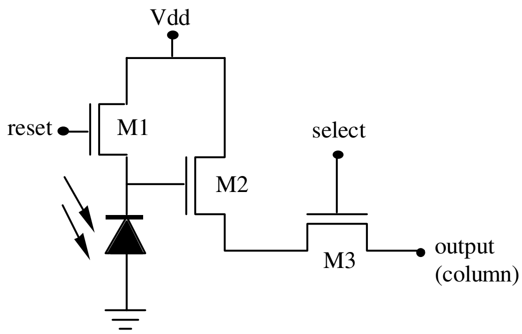


*Figure 2. 3-transistor active pixel*

A consequence of the large pixel array size is the large variation of the angle of incidence on the silicon. Therefore the pixel has to be designed as symmetric as possible. Microlenses are not used because of the dependency of the focus point on the angle of incidence. Instead, a technique is used to collect all charges generated in the silicon by the photodiode.[6] Figure 3 shows the principle. Light generates electrons inside the silicon at any place, also underneath the transistors and other structures. A small but effective potential barrier prevents the carriers from diffusing upwards to unrelated diode layers. Instead, all these charges diffuse until they are collected by the photodiode. This method increases the fill factor in the same way as a microlens, without the fall-off issues. This technique does also make most of the pixel area transparent, hereby reducing aliasing problems.

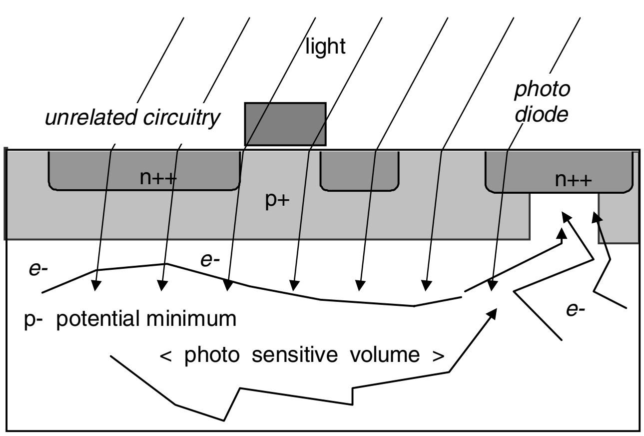


*Figure 3. Principle of high-fill factor pixel*

The pixel is covered by primary color filters. These are optimized for the best colorimetric performance. Special attention is paid in the design of the pixel to minimize crosstalk between the pixels. After color processing, such crosstalk would result in increased noise in the color channels.

## 4. Architecture

Figure 4 shows the architecture of the image sensor. The pixel array is driven by row selection logic from 2 sides of the array. This brings extra redundancy in case of defects. The column amplifiers read out the pixels and perform double sampling for reduction of fixed pattern noise.[7] The multiplexer brings the output to 2 or 4 output channels.

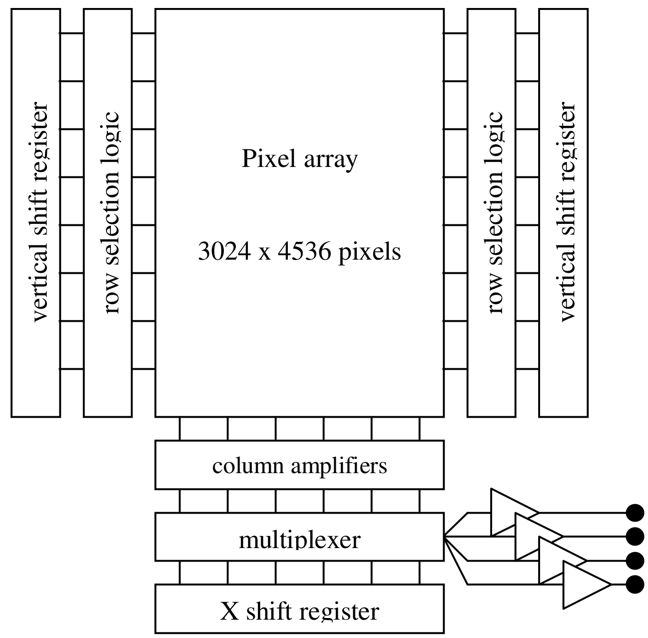


*Figure 4. Architecture of the image sensor*

Six different sub-sample modes are supported in the X and Y shift registers. The device can be read out either via 2 or 4 output buffers. The device also contains a power down mode.

A dark reference signal can be generated by a modified sensor timing. A few pixels of each column, or entire rows, are read out again after that they are reset. This generates a clean dark reference signal that can be used as a reference for external programmable gain amplifiers.

The device is packaged in a custom-made 49 pins pin grid array package. The glass lid contains a custom developed IR block filter, optimized for the best possible color response. The glass lid also features a chrome mask at the edges to avoid reflections inside the camera body.

## 5. Characterisation

Figure 5 shows the product of spectral response and fill factor as measured on a monochrome device. The peak of quantum efficiency x fill factor is 30%. For the color sensor, the curve has to be multiplied with the transmission curves of the color filters and the IR block filter of the cover glass.

Figure 6 shows the response curve of the device. The conversion gain is 15.3 µV/electron and the full well charge is 116900 electrons. The temporal noise is measured to correspond to 33 electrons. This yields a dynamic range of 71 dB. The linearity of the device is characterized as follows: the response curve deviates less than 3% from a linear fitted curve (through the origin) in the first 75% of the full range.

Table 1 summarizes the most important specifications of the device. Figure 7 shows a picture of the packaged device and a wafer.

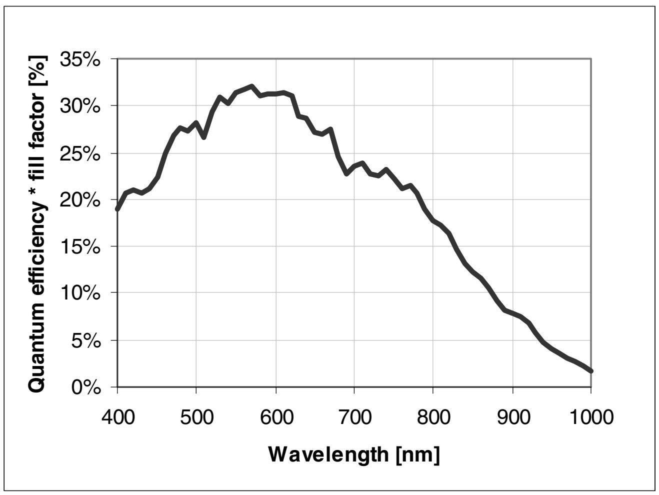


*Figure 5. Quantum efficiency * fill factor (monochrome sensor without cover glass)*

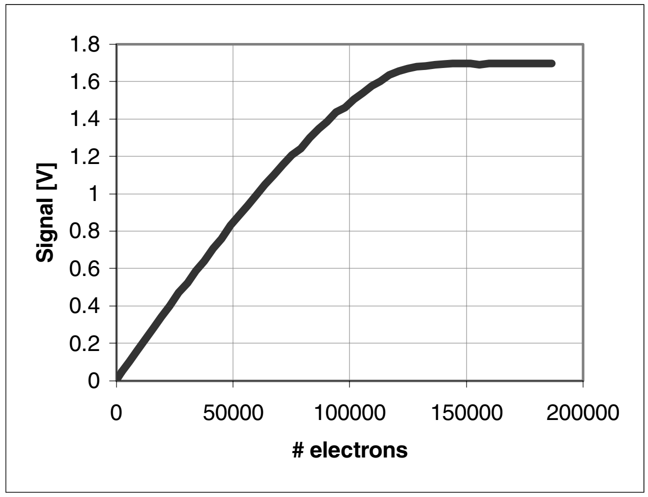


*Figure 6. Response curve*

**Table 1. Image Sensor Specifications**

| | |
|---|---|
| Max. Resolution | 4536 x 3024 pixels |
| Pixel area | 8 x 8 micron$^2$ |
| Fill factor * quantum efficiency | 30% (monochrome) |
| Color filters | Primary colors<br>Bayer pattern |
| Conversion gain | 15.3 µV/electron |
| Temporal noise | 33 electrons |
| Full well charge | 116900 electrons |
| Linear range | 75% Vsat<br>< 3% deviation from linear slope |
| Dynamic range | 71 dB |
| Fixed pattern noise | 0.14% RMS<br>(local : 32 x 32 pixels) |
| PRNU | 1% of signal at 50% Vsat (local) |
| MTF at Nyquist | 0.61 |
| Anti-blooming | $10^5$<br>(Charge spill-over to neighboring pixels) |
| Readout speed | 3.25 frames/s |
| Signal readout rate | Max. 15 MHz |
| Output channels | Via 4 or 2 channels |
| Sub-sample modes | 5 resolutions supported |
| Power dissipation | < 50 mA |
| Package | 49 pins pin grid array |

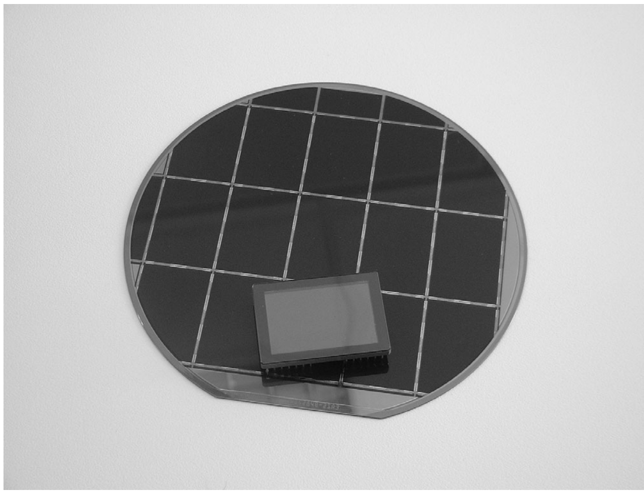

*Figure 7. Chip and wafer*

## Conclusion

A 35 mm format 14 Megapixel standard CMOS active pixel for digital photography is discussed. It has 71 dB dynamic range. The product of quantum efficiency and fill factor is 30%. It consumes 50 mA at its maximum frame rate of 3.25 frames/s. The large array is made by reticle stitching. Fall-off issues of microlenses are avoided by the use of a high-fill factor pixel structure.

## References

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## Biography

**Guy Meynants** received the Masters and Ph.D. degrees in electronic engineering from the Catholic University of Leuven, Belgium in 1994 and 1998, respectively. Between 1994 and 1999 he worked at Imec (Belgium) where he completed his Ph.D. on CMOS image sensors He worked on techniques to reduce fixed pattern noise and increase sensor sensitivity, and designed several image sensors. In 2000, he joined FillFactory as a co-founder, where he is active in the design and product management of CMOS image sensors. His has experience in design of image sensors and analog electronics, on-chip support electronics and large area CMOS imagers.