L² CMOS IMAGE SENSOR FOR LOW LIGHT VISION

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***Abstract* - A 1/1.8" format image sensor with 1280x1024 pixel array has been made in a new technology improving the electro-optical performance. The sensitivity is 2.5 times higher and the SF noise is reduced by 2.3 e-. Images taken under artificial night sky rendering confirm the potential of the new technology.**

1. INTRODUCTION

The electro-optical qualities of image sensor pixels have a great dependence on their ability to efficiently convert light (photons) to an exploitable electrical signal. The overall tendency of the imaging industry has been to reduce the size of the pixel in order to increase resolution and reduce the manufacturing cost. The consumer imaging segment is a spectacular example of this accelerated race to shrink pixels to a point where their width approaches the wavelength of visible light. However, reduction of pixel surface is significantly slower in some segments due to factors like the need for multiple transistors pixel architectures to achieve global or snapshot shuttering, or extremely high full well capacitance in order to achieve the highest possible linear dynamic range or Signal-to-Noise-Ratio. Technology advances applied to improving the performance of traditional front-illuminated CMOS imagers are yielding surprising results. While in the current case the light for an image is provided by a natural or artificial source, the imperfections of transforming photons to electrical signals becomes the major limiting factor. In order to achieve imaging in the lowest light, it is essential to minimise noise and maximise signal sensitivity characteristics of the sensor. The most important preoccupation now becomes Signal-To-Noise-Ratio or SNR.
In this presentation we show a Low Light CMOS Image Sensor (L²CIS) optimized for Night Vision systems [1] and suitable for any other applications requiring a combination of high sensitivity and dynamic (scientific applications, etc)

2. LOW LIGHT APPLICATIONS

The night vision market is dominated by systems based on image intensifier tubes. These solutions with a so-called "direct view" have a limitation when it is necessary to manage the resulting image for an operation by remote transmission or for recording. Patented e2v L3Vision™ CCD sensors offer this capability; the image signal is amplified on the chip while it is still in the charge domain allowing the sensor to operate in real time with sub-electron equivalent readout noise [2]. Solutions based on CMOS are an attractive alternative because they enable low power consumption systems and weight compatible with portable applications.

3. BASIC DEVICE ARCHITECTURE

e2v has developed a 1/1.8" format image sensor suitable for a large range of application including 2D barcode reading, machine vision, etc. It is composed around a 1280x1024 pixel array, made on CMOS imaging technology. The block diagram of the sensor is shown Figure 1. Based on system-on-chip approach, it consists in four groups of functions including pixel array, driving interface, timing generator and digital data post treatment. The image array is made of 5.3µm, 5T square pixels providing both Electronic Rolling Shutter (ERS) and Global Shutter (GS) capability. Peripheral circuits embed PLL block able to provide up to 480 MHz frequency from a single clock input. The frame rate is otherwise more than 60 Hz. Timing are provided inside the chip to operate the pixels, the 10 bits column ADC and the parallel output data synchronously.

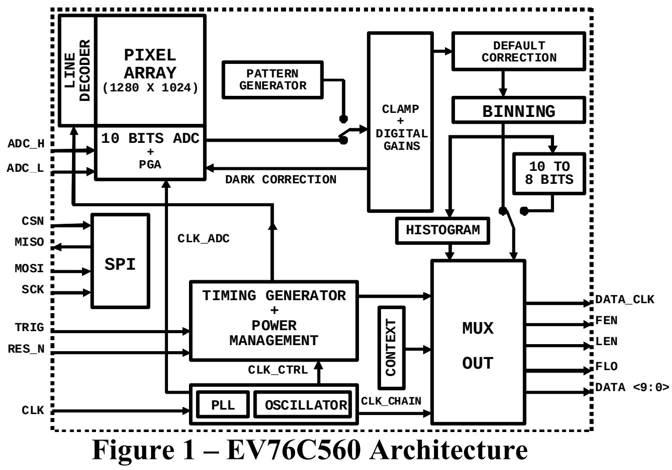

Figure 1 – EV76C560 Architecture

Features such as multi Region Of interest (ROI), Pattern generator, digital clamp, binning, defect correction and 10 to 8 bits compression are embedded. The context information including histogram, integration time, gains value, ROI parameters and all other user definable parameters can be used to setup automatically the sensor. The power consumption is less than 200 mW at 60 Hz and can be set down to 200 µW in standby mode. Taking as a starting point this performance proven image sensor, an experimental design to technology approach has been investigated to address low light vision applications.

4. LOW LIGHT CONDITIONS

A scene at night without moon light is still illuminated by natural light from the sky. The component of the polychromatic radiation comes from stars or distant galaxies, solar reflection of interplanetary particles but mainly from luminescence of chemical elements in the atmosphere, so-called Night Glow (NG) [3]. During clear night, the lunar contribution part is due to surface reflection of the sun light equivalent to 5500K daylight since the moon albedo can be considered uniform in the visible and NIR part of the spectrum [4]. Depending on meteorological conditions, the spectral photonic sterance of the night depends on the source of light as shown Figure 2 [5].

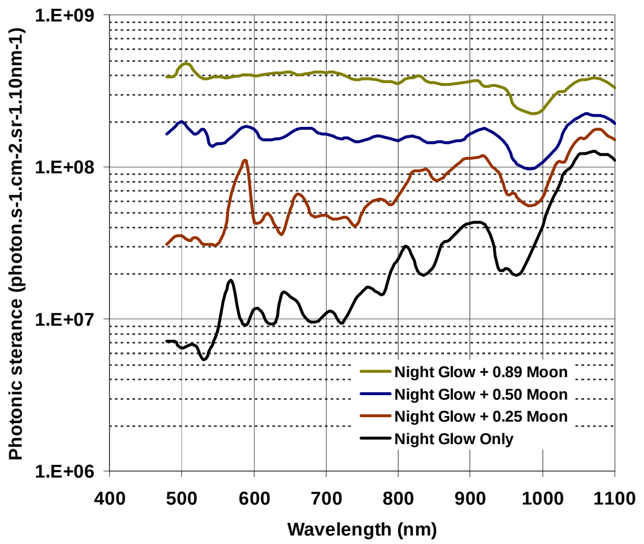

Figure 2 – Night sky spectrum

The available amount of photons P_h is calculated using the following formula:

$$P_h = \pi \sum E_\lambda \quad (\text{Photon.s}^{-1}.\text{cm}^{-2})$$

With λ the wavelength and E_λ the photonic sterance.

The corresponding photometric value M_V is deduced introducing the luminous efficacy and photon energy as following:

$$M_V = \pi \sum \frac{hc}{\lambda} E_\lambda . K_\lambda \quad (\text{lux})$$

with K_λ the scotopic luminous efficacy (lm/w), h Planck constant and c light celerity.

The corresponding night lighting conditions are summarized in Table 1, considering the e2v sensor, 80% lens transmission and F-Number = 1.

	NG No Moon	NG + 0.25 Moon	NG + 0.50 Moon	NG + 0.89 Moon
P_h (Ph.s-1.cm-2)	6.5E+09	1.6E+10	3.6E+10	8.3E+10
M_V (mlux)	0.8	4.0	13.4	33.0
Human Sight (meter)	~ 0	10	30	100
Photons/pixel (25 FPS)	15	36	81	186
Photons/pixel (60 FPS)	6	15	33	75

Table 1 – Night conditions

During night, the photonic signal is a few tens to several hundred photons at 25 FPS (Frame per Second) and down to few units to few tens at 60 FPS. It becomes now necessary to capture the majority of these photons in a range of sensor response as wide as possible, including near infrared (NIR).

5. SENSITIVITY INCREASE

Based on the physical properties of silicon where longer wavelengths penetrate deeper into the photo-sensitive conversion zone, it is often the case that thick epitaxial material is used to increase the Quantum Efficiency in the upper red and NIR wavelengths. Following the Beer-Lambert law, the absorbed energy has an exponential dependence of the material thickness as following:

$$I_{(\lambda)} / Io_{(\lambda)} = e^{-\alpha(\lambda)x}$$

with I and Io respectively the incoming and absorbed light, α the absorption coefficient, x the material thickness. To gain in sensitivity in NIR domain necessitates a significant increase of material thickness. However, thick material usually leads to MTF degradation through increased photonic crosstalk. Image quality is a combination of MTF and QE (so-called Detective Quantum Efficiency) where consideration must be given to both the space-domain and the frequency-domain, MTF becomes the second most important parameter. Deep depletion photodiodes with adapted silicon doping methods are used to recover MTF for long wavelengths in the upper non-visible part of the spectrum as shown Figure 3.

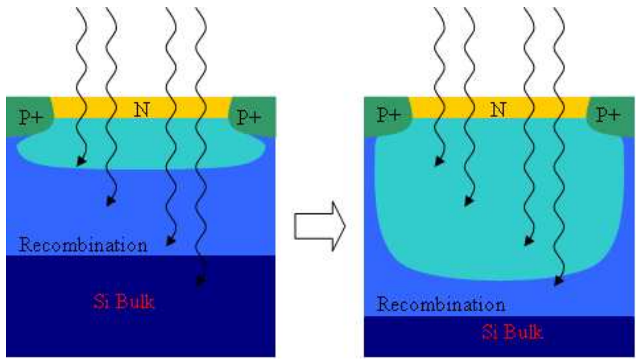

Figure 3 – Deep depletion approach

Considering a standard material, long wavelength photons generate electron-hole pairs near or into the bulk where they immediately recombine. Quantum Efficiency improvement with deep depletion approach is significant and benefic for night vision imaging, as the charges are generated within the depletion volume.

Quantum efficiency takes a direct part into the improvement of the Signal-To-Noise-Ratio or SNR as the useful signal is determined by photon to electron conversion efficiency. The other part of SNR is the noise itself. It characterizes the image quality at a certain level of light but also the detection threshold of the sensor generally considered when SNR=1. Noise sources in the image sensor readout and interfacing electronics are multiple and varied, and frequently have a direct relationship with temperature. An example is the dark current, which becomes dominant at longer integrating times. Another temporal noise is the result of kT/C effects that leave random residual voltages on sampling capacitors during the necessary clocking and resetting periods during the readout process.

Since it embeds its own amplifier, the pixel is a primary source of temporal noise. Using high gain to reduce the bandwidth can remove part of the noise but the consequence will be dynamic range reduction since the charge handling becomes limited. Photons are the quantum of energy converted into electrons within the photodiode whereas the noise floor is by nature a voltage. Each electron of noise at this level defines the level of detection of the image sensor. This is defined as the Noise-Equivalent-Illuminance or NEI representing the minimum Illuminance from which it is possible to produce a usable image. The factor CVF (Charge to Voltage conversion Factor in µV/e-) defines the translation of noise in the charge domain and applies into the SNR as follows:

$$SNR = \frac{QE.\ Nb_{Photons}}{\left(\frac{noise\ \ floor}{CVF}\right)}$$

Latest communications claim down to 2e- readout noise which pushes the limits of using solid state sensors in start light conditions [6]. Technology used for the design of the L²CIS permits the reduction of the source follower noise embedded into the pixel whilst the readout chain noise is kept low.

6. MEASUREMENT RESULTS

The sensor is fabricated using a 0.18µm 1P4M CMOS technology with specific development to adapt pixel amplifier. Specific diffusions implanted in the pixel transistors are optimized to decrease their noise. Individual contributors are quantified by operating specific timing diagrams and the measured values at 273K are listed in Table 2.

Noise contributors	Voltage	Charge	Part
Shot (40 ms)	0.09 mV	1.0 e-	10.1%
Transfer	0.10 mV	1.1 e-	11.3%
Pixel SF	0.22 mV	2.3 e-	53.1%
ADC	0.15 mV	1.5 e-	24.1%
Quantization	0.04 mV	0.4 e-	1.4%
Total $(\Sigma Ni^2)^{1/2}$	0.30 mV	3.2 e-	-

Table 2 – Noise contributors

Despite process improvements, the most important contributor remains the pixel amplifier formed by a source follower transistor (SF) however other noises which previously weighted in the second order appears now more prominent. The challenge of designing next generation night vision image sensors will be consider this new situation and focus on all noise contributors.

The transistor optimisation is combined with the adaptation of deep depleted photodiodes. The measured Quantum Efficiency is presented Figure 4 with reference to the previous state of the art.
The QE is 2.5 times higher in red and NIR parts which leads to an interesting gain in performance considering the emitting spectrum of night sky. Secondly the gain in the visible part of the spectrum reveals the efficiency of electrons collection within the photodiode deep depletion characterized as the internal Quantum Efficiency. Based on the noise and QE inputs the NEI can be calculated and convolved with the night sky spectrum as follows:

$$NEI = \frac{4F^2}{L_T}\frac{N_T}{\left[\frac{\sum QE_\lambda.E_\lambda.\lambda}{\sum K_\lambda.E_\lambda}\frac{A}{hC}\right]} \qquad \text{(lux.s)}$$

With L_T and F respectively lens transmission and F-Number, N_T temporal noise, λ the wavelength, QE_λ spectral Quantum Efficiency, K_λ the luminous efficacy, E_λ the photonic sterance, h Planck constant, C light celerity and A pixel area.

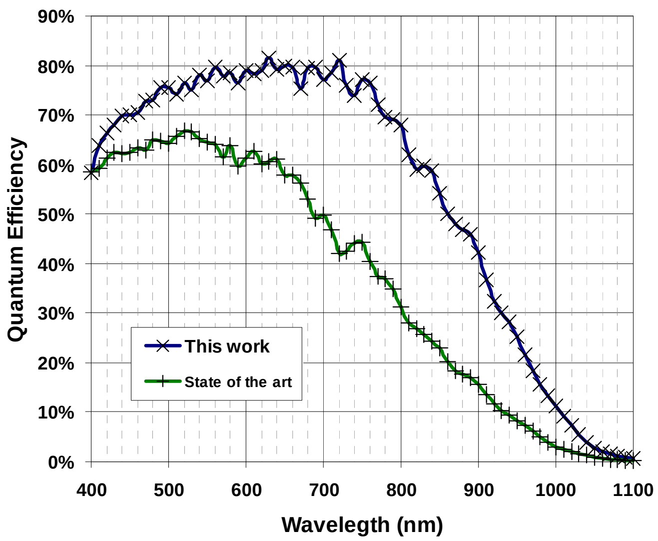

Figure 4 – Quantum Efficiency

The results are summarized in Table 3, considering 80% lens transmission and F = 1. With reference to Table 1, calculations predict the possibility of capturing scenes at 25 FPS only by Night Glow and quarter moon when NEI < M_V. To demonstrate the potential of e2v CMOS, a specific board embedding all image post processing has been developed. The board with the new sensor has been tested into e2v's night simulation tunnel. Images representative of the night sky spectrum and intensity are presented Figure 5, Figure 6 and confirm the above prediction.

	NG No Moon	NG + 0.25 Moon	NG + 0.50 Moon	NG + 0.89 Moon
Response e-/(lux.s)	1.6E+05	1.2E+05	9.4E+04	9.2E+04
NEI (mlux) 25 FPS	0.5	0.7	0.8	0.9
NEI (mlux) 60 FPS	1.2	1.7	2.1	2.2

Table 3 – NEI based on night sky

7. CONCLUSION

In this work we have presented a solid state solution for digitized night vision suitable for portable applications. We have successfully demonstrated image acquisition under very low light conditions. These results can be considered as a starting point for future designs considering potential improvement of noise contributors and quantum efficiency.

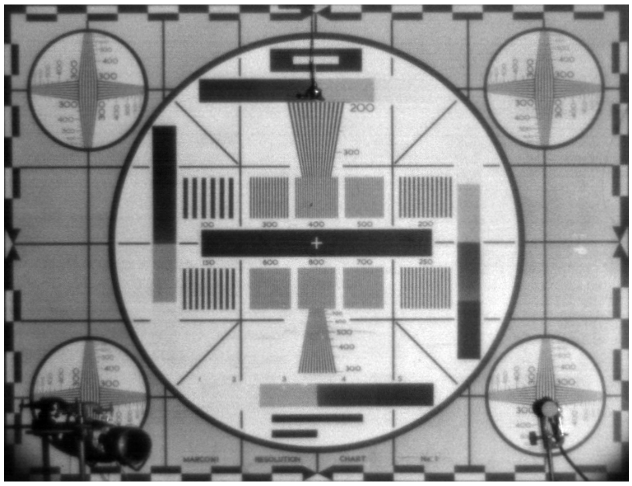

Figure 5 – Moonlight (25 FPS)

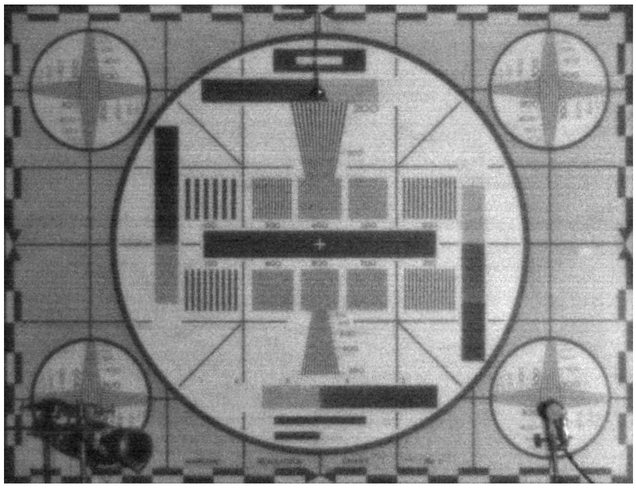

Figure 6 – Quarter Moonlight (25 FPS)

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