Night Vision CMOS Image Sensors Pixel for Sub-mililux Light Conditions

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Abstract -**This paper presents A CMOS Image Sensor (CIS) pixel which can give acceptable images in very low illumination conditions down to less than 1 mililux. This paper reviews the considerations of a CIS pixel optimized for sumbililux sensing, discusses several optimization factors, and the way they were implemented, and finally presents performance parameters and images taken with a camera which uses a sensor based on this pixel.**

Keywords: **Low Illumination, Night Vision, CIS**

I. INTRODUCTION

A CMOS Image Sensor (CIS) which can give acceptable images in illumination conditions of less than 1 mililux can be literally considered as "seeing in the darkness" [1]. 1 mililux is associated with a moonless clear starry night, whereas 0.1 mililux is a moonless overcast night. Such performance may be required, for instance, in security applications. In the past, this could only be achieved by using Image Intensifier (II) technology [2].

Sensing in extremely low illumination levels requires optimization of the camera system in general, and the pixel in particular, to perform in photon-starved conditions. Good optics with small F# is needed, as well as smart image processing to correct errors and maximize the image quality. This paper focuses on the pixel optimization.

A relatively large pixel is preferred, in order to collect as many photons as possible. Near Infrared (NIR) response is important [3] since in night vision, a significant part of the illumination is shifted to the red and the NIR. Pixel optics including microlens and anti-reflecting-coating (ARC) should be optimized as well. In such illumination we expect up to a few photons per frame (in a 30 frame per second standard video), so that the pixel noise should be 1 electron or less, per frame. To achieve such low noise one needs to maximize the pixel conversion gain on the one hand, and reduce the residual 1/f noise of the pixel output after correlated double sampling (CDS) as much as possible, on the other hand. These two requirements are not easily simultaneously optimized, for a pixel with large photodiode.

II. PIXEL OPTIMIZATION

The pixel for ultra low light application is a 4T pixel which was optimized for the following features

1. Pixel Dimensions
2. NIR response Optimization
3. ARC optimization
4. Microlenses
5. Residual 1/f noise reduction
6. Dark Current Noise
7. Maximizing Conversion Gain (CG)

We will discuss below the optimization done for each of these features.

Pixel dimension was carefully chosen. Obviously, larger pixel can collect more photons. However, too large pixel will limit the possible resolution, and the achievable microlens efficiency. A 10µm pixel was found to be a good choice for both.

In order to enhance the red and NIR response of the pixel, a thick Si epi layer was used as starting material. For the first generation of the camera a 12 µm epi was used. Our more advanced pixel is using our recently reported [4] technology of an improved MTF NIR sensitive pixel on a thick high Resistivity p-epi substrate. A comparison of the QE curves of the different starting material is shown in Figure 1.

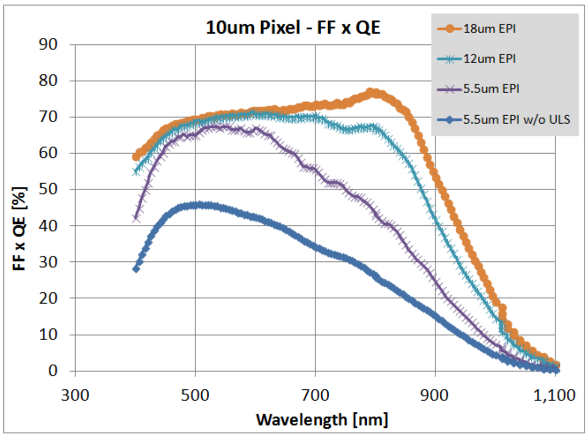

Figure 1: Quantum Efficiency vs. Wavelength for LONiS with different epi thicknesses, 5.5 µm, 12 µm & 18um, showing the improved response in NIR and micro-lenses contribution

The ARC was tuned to minimize the reflectance from sensor surface. It turns out that an important outcome of a well optimized ARC is the reduction of the "etalonning" effect of the backend dielectric stack.

The larger the pixel, the higher should be the proper microlens to be used. A special microlens (super thick microlens) was used to achieve sag of 3µm, as shown in figure 2.

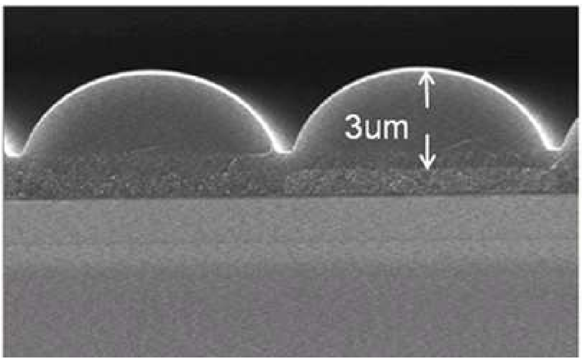

Figure 2: Cross section of Super-thick micro-lens - SEM image

The QE boost achieved by the microlenses is also shown in figure 1.

A 4T pixel with correlated double sampling removes the kTC noise and leaves noise which is usually attributed to the residual 1/f noise of the pixel's Source Follower (SF) output transistor.

In order to minimize the noise of the SF – a transistor with a relatively large area gate is needed, and with well tuned implants. The first generation pixel is using TowerJazz low noise SF, having residual noise of 120µV RMS. Even better noise performance can be achieved with a buried channel SF. Such a transistor has negative threshold and requires dual Vdd supplies for the pixel. Such SF has lower noise (down to 80µV RMS) and better noise distribution as shown in figure 3.

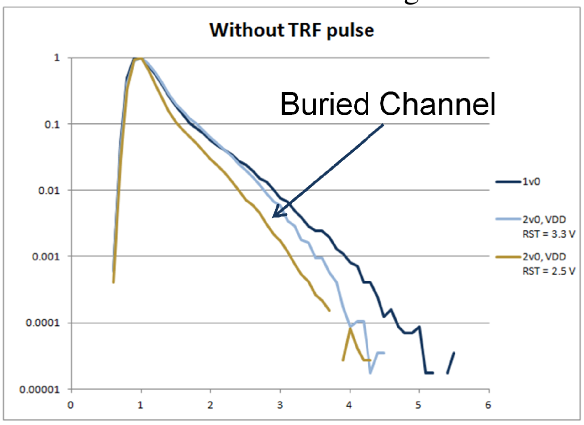

Figure 3. Noisefloor distribution comparison of pixels with surface and buried channel source follower transistors

The dark current is another source of temporal noise. This pixel has dark current of less the 30 e^{-}/sec in room temperature, which gives less than 1e^{-}/frame. The dark current distribution in room temperature is presented in figure 4.

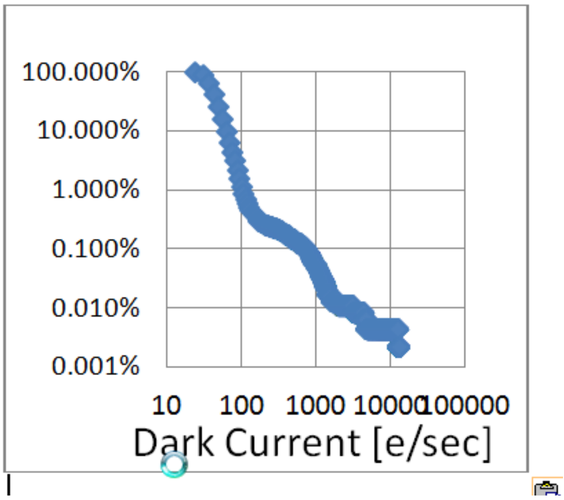

Figure 4: Dark current survival plot for LONiS sensor. The average dark current is 30 e/sec at room temperature

The camera enables temperature stabilization which reduces the dark current by an order of magnitude by cooling to 0C.
An improved TowerJazz process can achieve much lower DC of 1-5 e^-/sec /μm^2 at 60C, implemented on an N-substrate material. However, from obvious reasons it is still challenging to maximize QE in the NIR for this process.
Maximizing the CG for 10 μm pixel is the next challenge. Though conversion gains of 190μV/e^- and more, are already reported [5], these are for much smaller pixels. Maximizing the CG requires the largest possible SF gain, and lowest possible capacitance load on the floating diffusion node. The optimized SF has very small body effect and SF gain exceeds 0.9. In order to reduce capacitance load the floating diffusion junction area can be minimized and so is the reset gate. However, having large photodiode requires wide transfer gate to keep perfect charge transfer. The SF gate is also relatively large as previously explained. For both transistors the dominant capacitance is due to fringing fields from the poly to the active area, and not due to channel charge. The reasons are the perfect charge transfer for the transfer gate, and the large SF gain for the SF gate. Thus, smart layout of these gates can minimize this fringing capacitance. Example of such layout (only poly and active area are shown) is presented in figure 5. Another important source is the backend metallization of the pixel, which should be carefully designed and simulated to minimize its parasitic capacitance load on the floating diffusion node.
The backend capacitance is a major factor in the overall parasitic capacitance and is responsible for about 50% of the floating diffusion capacitance. Based on later simulations a better metallization scheme was found, expected to increase the CG from 120 to 140 μV/e^-

III. Pixel and Camera Results

The pixel was developed on a test vehicle and finally was implemented in a sensor (LONiS) and was integrated into a low light camera. The LONiS was designed by Anafocus (Spain) and was integrated into a camera by DVtel (Israel) with cooperation with Elbit Systems (Israel). The camera and the packaged LONiS are shown in figure 6. The results shown below are for the first generation of this pixel, with non optimized ARC, surface channel SF, and first metallization optimization. Starting Material is 12 μm epi 30Ω·cm (Non High Resistivity). The pixel performance parameters are listed in table 1.

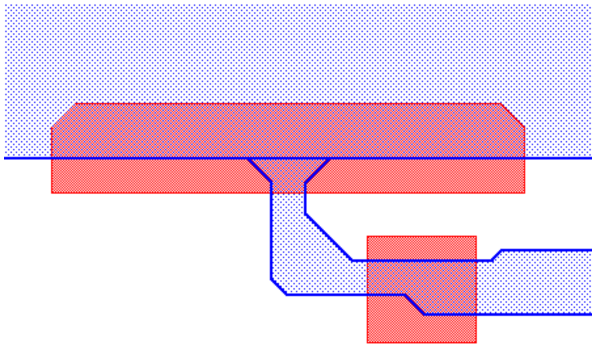

Figure 5: Layout used to minimize floating diffusion fringing capacitance of the transistors. Active Area and Poly are shown.

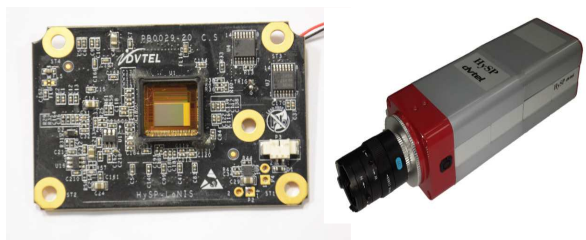

Figure 6: LONiS sensor and its board, and DVtel camera based on LONiS sensor.

Noisefloor distribution in two different systems is shown in figure 7.
These results are in line, or better, than the competing low light cameras in the market [1,3].

Parameter	Value	Units
Response (Green 523nm)	48	Volt/Lux·sec
Conversion Gain	120	µV/e$^-$
PRNU	0.4	%
MOVS	1.6	Volt
Full Well Linear	13.3	Ke$^-$
Temporal Noise floor	120	µV RMS
Dynamic Range	>78	dB
Average Dark Current (30C)	30	e$^-$/sec

Table 1. Pixel performance parameters summary

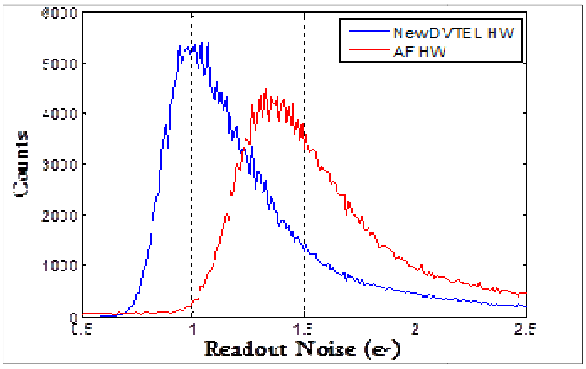

Figure 7 Readout noise distribution of LONiS measured by two different hardware systems

In figure 8 we present images taken in very low illumination levels down to 0.13 mLux, showing the performance of this camera in illumination conditions close to full darkness. These images were taken in 37C, 30 fps, with F1.2 lens.

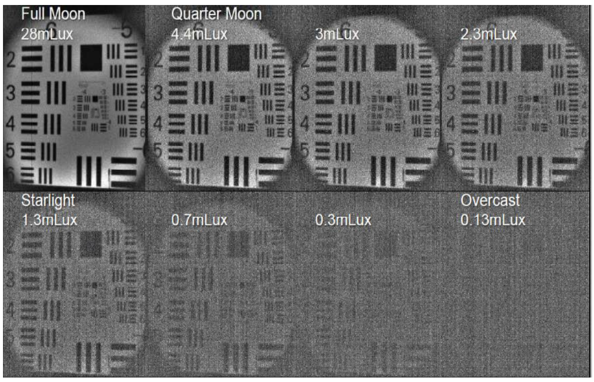

Figure 8: Barchart photos with different illumination levels. Raw data without any image processing. Images were taken in 30fps, 37C and F1.2 lens. 12µm epi, no ARC

IV. SUMMARY

We presented the development of pixel ultra low illumination levels. The sensor based on this pixel gives acceptable images for illumination levels smaller than 1 mLux. As far as we know at this time this is the best performing sensor in ultra low light levels. Several improvements were developed and discussed above, namely, an optimized ARC, higher conversion gain, lower temperature, and high resistivity thicker epi. These improvements are expected to make the 2nd generation of this camera more sensitive and outperform the benchmark of II technology.

We want to thank DVtel, Elbit systems, and Anafoucs for the joint work, for the photo images, and for taking part in the characterization of the pixel. We would also like to thank HySP consortium of Israel's Ministry of Commerce for their support of this development.

V. REFERENCES

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