ORION sensor 10um 66Mpixel high dynamic range and sub-electron dark noise image sensor

Jose Segovia[1], Alberto Villegas[1], Rafael Dominguez[1], Loli Pardo[1], Alex Charlet[1], Luis Alba[1], Sony Cherivan[2], Jason Nottingham[3], Len Colavito[2], Ana Gonzalez[1], Ángel Rodríguez-Vázquez[4]
1 Teledyne Anafocus, Isaac Newton 4, Planta 5 SE-NE, 41092, Sevilla, Spain
2 Teledyne Princeton Instruments, 3660 Quakerbridge Rd, Trenton, NJ USA 08619
3 Teledyne Photometrics, 3440 E Britannia Dr. Suite 100, Tucson, AZ USA 85706
4 Institute of Microelectronics of Seville (IMSE-CNM), CSIC-Universidad de Sevilla, Spain
E-mail:jose.segovia@teledyne.com

Abstract – This paper presents a large scale 8k x 8k CMOS image sensor performing low noise and High Dynamic Range (HDR). The sensor embeds a 10 µm pixel with dual conversion gain featuring full well capacity (FWC) higher than 120 Ke- and sub-electron dark noise within the same image, providing > 100 dB dynamic range. The ORION sensor is back side illuminated allowing quantum efficiency (QE) greater than 90% with a dark current lower than 0.006 e/sec at -22 ºC. The device includes flexible operation modes enabling rolling shutter and global shutter, with different ADC resolutions to exchange noise performances and speed, being suitable for different low noise applications.

Keywords – CMOS image sensor, HDR, dark current, FWC, QE.

I INTRODUCTION

The CCD image sensors have been used extensively for low noise scientific and astronomy applications [1], given the low dark current, high quantum efficiency, low temporal noise and large achievable array sizes with large pixels.

However, CMOS image sensors are advancing in low noise applications based on enhanced pixels and readouts [2][3]. Scientific and astronomy applications require very large full well capacity to capture in the same scene elements with a wide variation of illumination across pixels. Large pixels are eventually needed to increase pixel sensitivity, a key parameter in astronomy and science. Large pixels, along with large format resolution result in very large sensor dimensions.

The sensor in this paper improves the architecture reported in [4] and employed in [5]. It achieves 85dB with 0.7 e- rms readout noise owing to the combination of different strategies including noise model fitting, multi-stage ADCs, over-sampling and CMS. Additionally, incorporates dual conversion gain achieving 101 dB with 1 e-rms readout noise providing high dynamic features comparing to single conversion gain sensors [6].

II ARCHITECTURE

The ORION sensor includes a 5T pinned-photodiode dual conversion gain 10 µm x 10 µm pixel, providing high gain, low gain for HDR conversion modes. The back thinned wafer is a stitched device consisting of 1620 x 1620 pixels tiles, in a 5 x 5 tile configuration depicted in Fig. 2.

ORION sensor digitizes pixel signals with a novel two-stage ADC architecture, based on Incremental ADC and Single-Slope ADC depicted in Fig. 2. The design allows programmable reconfiguration of bit resolution and conversion time, providing a trade-off between ADC noise and frame rate. The first stage ADC is an Incremental ADC which resolves the MSB bits of the digital word. It can be programmed to resolve 4, 5 or 6 bits. The incremental sigma-delta ADC is operated to be able to perform analog CDS operation, integrating the reset level and the signal level in opposite directions. A second stage ADC is a single-slope ADC, which resolves the 10 LSB bits of the word.

The ORION can utilize 14-bit High Gain and 10-bit Low Gain conversion to achieve HDR operation. Correlated double sampled (CDS) can be performed in either the analog or digital domains. Configuration allows trade-off of power, frame rate and noise performance. This allows for optimizing large level signals dominated by shot noise. With external (digital domain) CDS, multi-sampling (CMS) is available to further reduce temporal noise to sub-electron levels. When combined with HDR readout, a dynamic range of over 100dB is realized in a single exposure.

The >64Mpixel sensor consists of one sensor per wafer in a 200mm wafer. To achieve acceptable yield in a wafer scale sensor, special design rules for manufacturability have been employed. In the pixel array only one line per pixel per layer is used, avoiding stacked lines between consecutives layers. The use of at least double via in the entire chip is mandatory, apart from extra rules in the periphery extending the metal paths width and space. Additionally, a technique is used to insert spare redundant readout channels every 90 default readout channels. In case one readout channel is defective, it is replaced by the spare channel.

Fig. 3 shows the packaged back illuminated device. The die measures approximately 91.4 mm x 92.5 mm and the multi-layer ceramic package is 173.0 mm x 166.5 mm (24 cm diagonal). Extreme care has been taken during the design phase to minimize stress gradients across the sensor die as well to maximize thermal conduction away from the die since it is intended to be attached cold finger working at -25 ºC.

The ORION sensor implements a low power mode that can be activated to reduce power when long integration time is used. This function allows the camera to reduce the sensor temperature bellow -25 ºC, while at the same time preventing the 'glow effect', which is caused by light emission inside the sensor that can be collected by the photodiode and presents as an undesirable source of dark current. The circuitry periphery is covered by aluminum layer, and additionally, pixel array is surrounded by a vertical aluminum trench to reduce glow effect.

III MEASUREMENT RESULTS

The ORION sensor can support a wide range of operating modes. Table 1 shows the most representative operating modes in the sensor within the main specifications like frame rate and dark noise. In high conversion gain, the sensor is delivering less than 1.6 e-rms read noise with very low Random Telegraph Noise (RTN) as seen by the dark noise distribution shown in Fig. 4. A frame rate of approximately 22 fps is obtained reading out the full 8120 x 8120 frame with a row conversion time on the order of 5.4 us. Smaller regions of interest (ROI) can be programmed increasing the frame rate according to the row conversion time. Global shutter is performed doing true external CDS, subtracting reset image and signal image, increasing the data throughput with only a reduction of frame rate less than 14%.

Table 2 reports the electro-optical performances measured in these modes**.** Very low dark signal non-uniformity (DSNU), 1.5e- and 16e- in high/low gain respectively, and low photo response non-uniformity (PRNU), 0.24% and 0.09% in high/low respectively are observed in 14 bits rolling shutter mode. Full-well capacity in the device tested measured to be greater than 15,000 e- and 125,000 e- in high/low gain respectively. Sub-electron noise of 0.7 e-rms is achieved with correlated multisampling technique (CMS). High dynamic range larger than 100dB is achieved with 16b conversion of high gain and low gain component. Fig. 5 depicts the ORION quantum efficiency, it shows a peak QE of higher 94% at 550nm, with good wide spectrum at NIR wavelengths: 53% at 850nm and 35% at 925nm.

Fig. 6 shows high gain and low gain dark image after DSNU correction. Dark current has been measured at -22 ºC resulting in 0.0058 e/sec. Dark current is observed to decrease by half every 4.1 ºC.

The effect of activating the low power mode is noticeable at very low temperatures, <25 ºC, with large exposures as shown in Fig. 7, where the images are obtained using 10 minutes integration time.

IV CAMERA INTEGRATION

The sensor has been integrated in a deeply cooled CMOS camera for ground-based astronomy and scientific applications, depicted in Fig. 8. The sensor is embedded in a vacuum chamber made of a permanently evacuated metal construction with all hard metal seals. The ORION sensor is cooled using Thermo Electric Cooling (TEC) modules located within the sensor vacuum chamber. Cooling a sensor with a thermal load of this magnitude generally requires the employment of multiple cooling modules. In this case 4 modules each driven by a 2 stage TEC were needed. Each of the modules are liquid cooled and together they drive the sensor to < -25 ºC.

As achieving a minimal thermal gradient across the sensor was a priority, each of the cooling modules are independently driven to compensate for uneven head loads created on the sensor by readout circuitry etc.

All the liquid cooling blocks are plumbed in parallel and have matched flow characteristics. The camera utilizes a 4-lane CoaXPress link operating at up to 12.5 Gbit/s to the host PC via a Dalsa Xtium2™-CXP PX8 quad-channel PCIe frame grabber. Fig. 9 shows two example images of the space already obtained with ORION sensor in the camera.

V CONCLUSIONS

The ORION 8k x 8k low noise wafer scale CMOS image sensor has been presented. Measurements from this >64Mpixel sensor has been reported demonstrating exceptional electro-optical performance characteristics for such a large device. Read noise of less than 0.7 e-rms with very low RTN, dark current bello 0.006 e/p/s at -22 ºC is observed. The ORION sensor is embedded in a camera with vacuum chamber and TEC devices that allows colling the device at -25 ºC providing very low dark current even with long integration times thanks to the low power technique and the design considerations taken to avoid glow effect.

REFERENCES

[1] Lesser, M., "A Summary of Charged-Coupled Devices for Astronomy," JSTOR 127(957) 1097-1104 (2015).

[2] A. Boukhayma et al.., "Noise Reduction Techniques and Scaling Effects towards Photon Counting CMOS Image". *Sensors 2016*, pp. 423-428, Apr. 2016.

[3] P. Seitz and A.J.P. Theuwissen. *Single-Photon Imaging*, Springer: Berlin, Germany, 2011.

[4] Fenigstein et al., "Night Vision CMOS Image Sensors Pixel for Sub-mililux Light Conditions". IISW 2015, pp. 373-376, June 2015.

[5] A. González-Márquez et al. "Design Considerations for A Low-Noise CMOS Image Sensor". in *IST Electronic Imaging*, Feb. 2015.

[6] J. A. Segovia, A. Rodríguez-Vázquez, et al., "A 5-Megapixel 100-frames-per-second 0.5erms Low Noise CMOS Image Sensor With Column-Parallel Two-Stage Oversampled Analog-to-Digital Converter", IISW 2017.

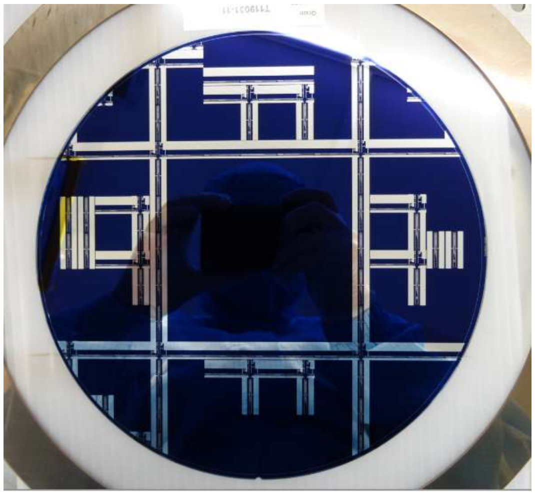


Fig. 2. Wafer scale 8k x 8k image sensor with 10um pixel.

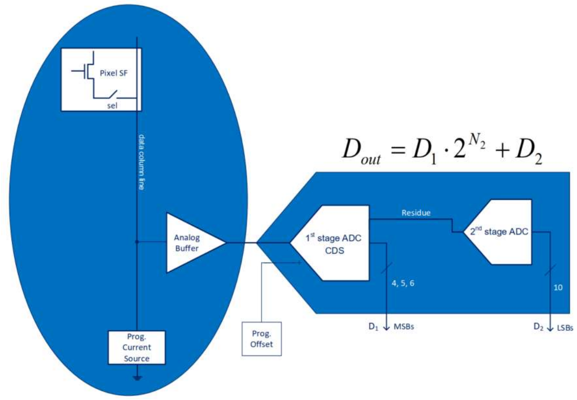


Fig. 1 Two-stage ADC showing the split Incremental / single-slope architecture.

Fig. 3. Packaged back illuminated >64Mpixel ORION device.

Table 1. Sensor Operation modes

Mode	ADC bit depth	Shutter Mode	Frame Rate (full frame)	Read Noise (high/low gain)
14b Standard RS	14b high or low gain	Rolling	22 fps	< 1.6 / < 12 e- rms
14b Standard GS	14b high or low gain	Global	19 fps	< 2 / < 12 e- rms
16b Standard RS	16b high gain	Rolling	6 fps	< 1.1e- rms
18b HDR RS	14b high + 14b low gain	Rolling	1 fps (with 16x CMS)	< 0.8 e- rms

Table 2. EO measures 4b RS high/low gain and 16b low gain.

EO Parameter	14b High Gain RS	14b Low Gain RS	14b/14b HDR RS	16b/16b HDR RS	14b High Gain GS	14b Low Gain GS	14b HG RS CMS=16
DSNU (e-)	1.52	15.95	3.77	0.36	1.52	15.95	0.38
PRNU (%)	0.24	0.09	0.10	0.14	0.24	0.09	1.07
FWC (Ke-)	>15	>125	>120	>120	>14.5	>115	>13.8
Dark Noise (e- rms)	1.49	11.53	1.64	1.02	1.92	11.96	0.71
DR (dB)	80.05	80.70	98.17	101.54	77.56	78.17	85.22
SNR (dB)	41.76	50.96	50.79	50.79	41.61	50.60	41.59

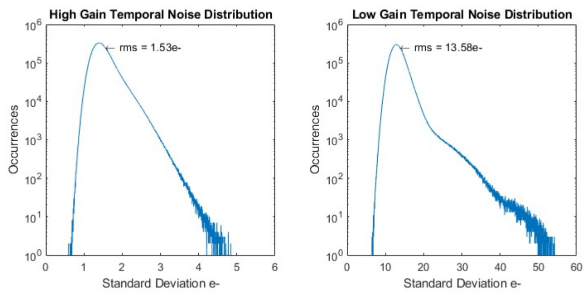


Fig 4. High and low gain dark noise distributions in 14 bit RS.

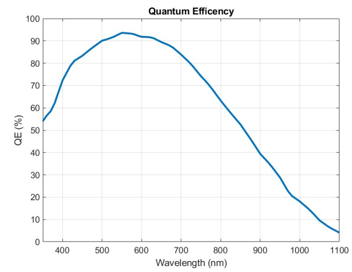


Fig. 5. Quantum efficiency measured from 350 to 1100 nm.

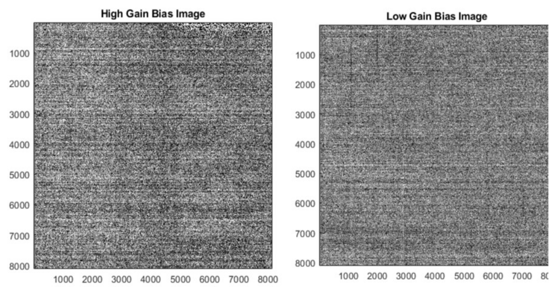
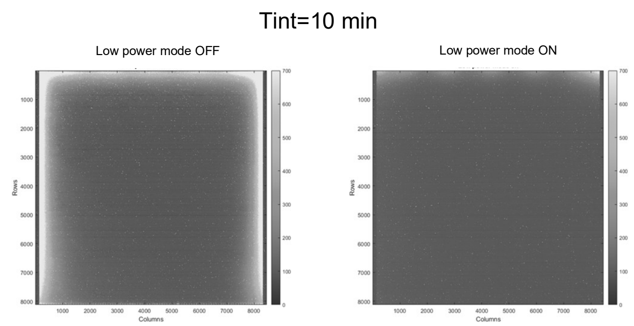


Fig. 6 High gain and low gain bias images.



(a) (b)

Fig. 7 Long integration Tint=10 minutes dark images (a) Standard Mode (b) Using Low power mode with glow effect reduction.

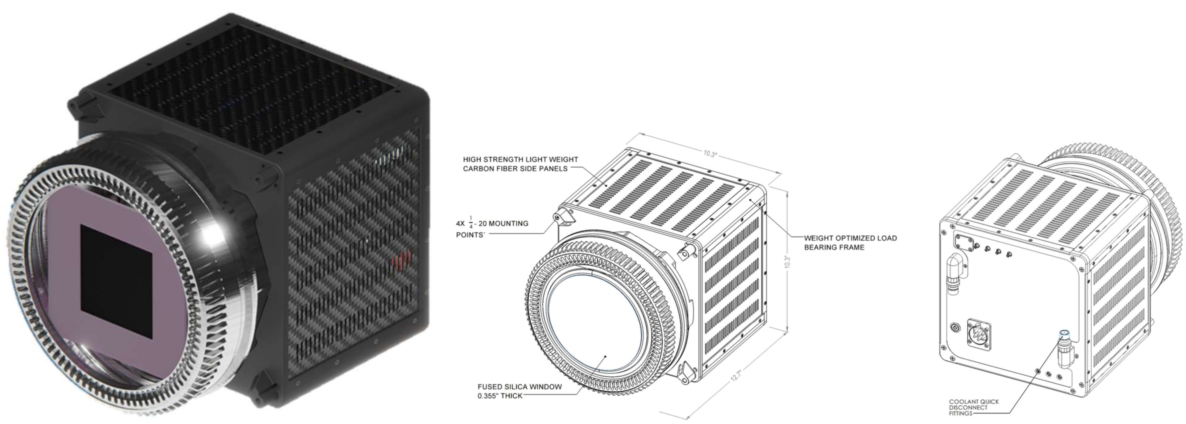


Fig. 8 Front/Exterior and back of the deep cooling camera with ORION inside.

Fig.9 Astronomy example images obtained with ORION