5 Minutes Integration Time Deep UV Pixel Development for "Ultrasat" Space Mission

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***Abstract*—This paper presents the pixel development for the Deep-UV sensor of "Ultrasat" space telescope. The 9.5um Pixel achieves 95dB dynamic range, QE of 80% at 240nm and Dark Current of 0.02 e/sec at -50C.**

Keywords—ultraviolet, Back Side illumination (BSI), Dark Current, Scientific Imaging

I. Introduction

The ULTRASAT Transient Astronomical Satellite [1,2], led by the Weizmann Institute of Science (WIS) and the Israel Space Agency (ISA), is planned to have a broad scientific impact across the fields of Gravitational Wave (GW) sources, supernovae, variable and flare stars, active galactic nuclei, tidal disruption events, compact objects, and galaxies. ULTRASAT is expected to be launched into GEO orbit in 2026 by NASA, carrying a UV space telescope with a large field of view, extremely sensitive in the wavelength range of 220 and 280 nm.

A custom 22.5-Mpixel UV BSI CMOS Image Sensor was developed to serve at the heart of this telescope. The camera is composed of 2x2 22.5-Mpixel sensors, utilizing a total sensing area of 90mm x 90mm.

To collect the weakest signal from the far end of the universe, the sensor integrates each frame for 5 minutes(!). Extremely low dark current is crucial for such long integration, which was achieved by careful pixel and array design, and by cooling the sensor to -70oC.

Pixel design's main challenges are: (1) a dynamic range larger than 92dB, (2) very high QE in the UV range, with an average larger than 60% in the 220-280nm range (3) extremely low dark current, less than 0.026 e/sec at -70^{o}C.

A 9.5µm Dual-Gain Rolling-Shutter Pixel (Fig. 1) was designed and fabricated using the 180nm CIS BSI process of Tower Semiconductor. Pixel and process integration were optimized to meet these requirements.

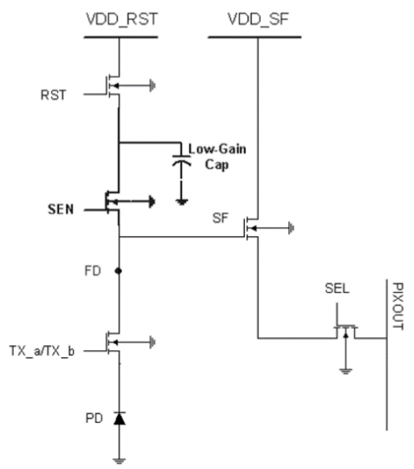

Fig. 1. The Pixel Schematics

II. Pixel Design – High Dynamic Range

The high dynamic range of 95dB was established by the combination of (1) high conversion gain (100µV/e), (2) low noise source follower and (3) Full Well of 150Ke.

A special Transfer Gate and Floating Diffusion design [3] was used & optimized for a 2-Dimensional stitched process. A delicate adjustment of the layout was performed to enhance robustness to the allowed masks alignment variations, with no compromise on resulting device performance.

A dedicated Low-Noise Source Follower (SF) with a large enough gate area was chosen to find the optimal combination of tight noise distribution & low enough SF capacitance.

The Drain supplies of the pixel 'RST' & 'SF' transistors were separated to allow optimal operation under low light conditions (keeping the SF at Saturation mode for signal levels close to dark).

300 sec integration time puts a unique challenge to this application; maintaining very high Full Well at the Photodiode, while allowing very good low-light linearity, requires careful optimization of the pixel layout, operation & process.

Photodiode Pinning Voltage, Transfer Gate Isolation & Floating Diffusion doping affect some of the key pixel parameters: Full Well, Signal Linearity, Anti-Blooming ability and sense-node capacitance.

These aspects were widely explored during the pixel development phase, and the optimal combination was applied on the ‘Ultrasat’ pixel.

III. Dedicated UV Anti-Reflecting Coating

In Backside illumination sensors there is more freedom to select ARC (anti reflecting coating) materials and thicknesses, compared to front-side illumination sensors, where the various layers which are a mandatory part of the front-end devices also affect the light absorption and reflection. The two main considerations for choosing a good ARC are: (1) High QE within the selected bandwidth, (2) Formation of an excellent surface passivation.

For Ultrasat mission, the goal was to optimize QE in the 220÷280nm band and try to minimize the QE for longer wavelengths.

The ARC must be solely composed of “Fab-Friendly” materials. In addition, it should not consist of too many layers/processing steps. Thus, we chose to use up to 6 layers for the ARC layers stack.

The 1st layer takes care of surface passivation. A well-known high-K material which is negatively charged, creates a thin accumulation layer of holes on the epi surface and eliminates dark current generation which could have been caused by surface states and dangling bonds.

Optical simulations were used to define the properties of the complete ARC layers stack and compare their expected performance.

Material types & layers thickness were carefully tuned to achieve maximal transmittance at the selected wavelength band and the typical incident angle of the telescope optical system. Several ARC options were chosen and implemented on a test sensor.

The chosen “UV-2” coating achieves Peak QE of 80% at 240nm and average of more than 60% for the 220-280nm band (Fig. 2,3).

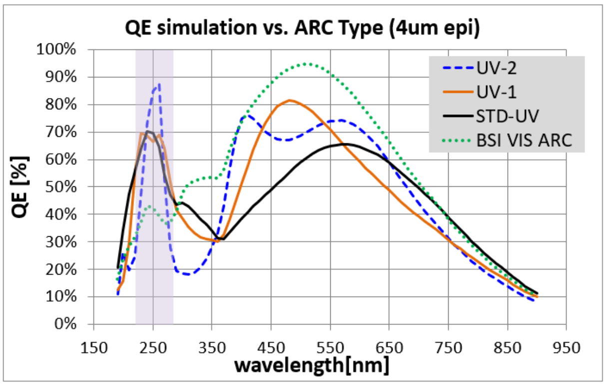

Fig. 2. Simulation of Quantum Efficiency vs. Anti-Reflective Coating Type. “STD” UV-ARC is compared with two options of UV-tailored ARC for the Ultrasat range of interest (220-280nm). The STD BSI ARC for visible light is also presented as a reference

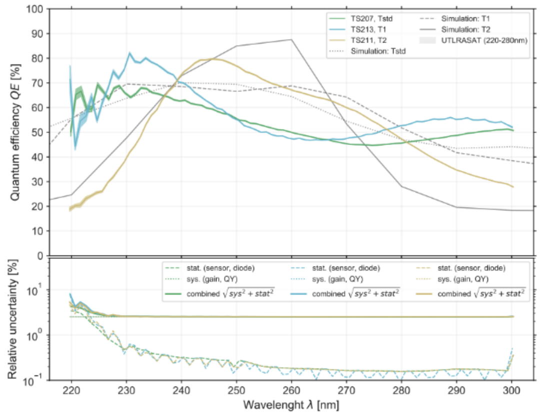

Fig. 3. Actual QE measurements of the 3 ARC flavours (UV-2 or “T2” was the chosen one)

IV. Dark Current Optimization & the ”Optical Trench”

During the pixel and process development stage (conducted on a pixel design development sensor), we encountered an effect of light emission from on-chip peripheral circuitry (Fig. 4,5).

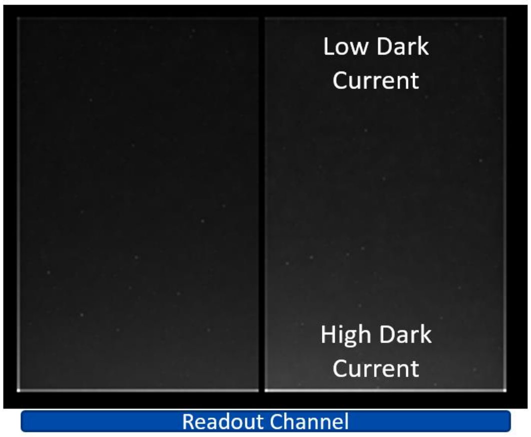

Fig. 4. Dark Image Affected by Nearby Circuits emission (Captured on the Development sensor, processed with no “Optical Trench”)

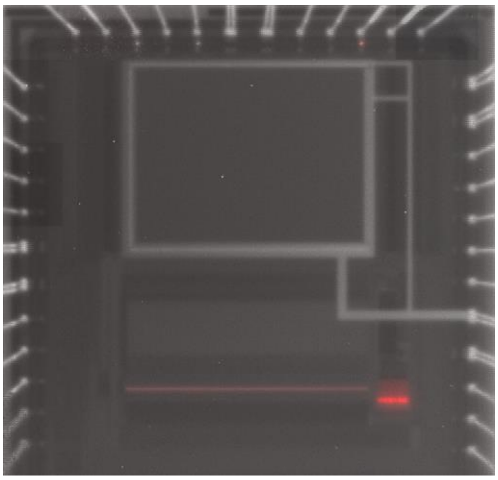

Fig. 5. Infrared Emission top image of the development sensor showing the glowing circuits. The Bright frame around the pixel array is the “Optical Trench”

This effect, historically known from scientific CCD sensors as "Amplifier Glow" [4], appears to be present and significant in high-end cooled BSI CIS as well, especially when observing faint light sources during long integration times[5].

Due to the high refractive index of the silicon versus the ARC/external media on one side and dielectrics of the CMOS backend on the other side, the emitted IR light is waveguided in the thinned epi-Si layer (Fig. 6).

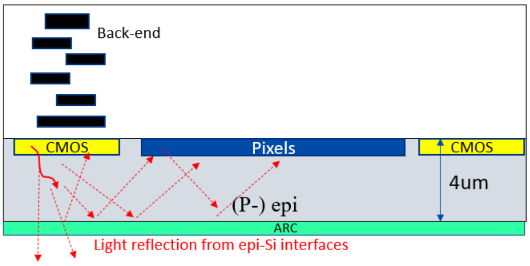

Fig. 6. NIR photons emission from the peripheral circuits

With no barrier to stop them, the emitted IR photons would slowly absorb along the pixel array epi layer, leaving a clear pattern of Dark Current gradient.

Different methods were used in the past to minimize this phenomenon (shut-off unnecessary circuitry blocks during exposure time, place other blocks as far as possible from the pixel array) but none of them could fully eliminate it.

Comprehensive analysis of this phenomenon led to a unique process development of a physical barrier that blocks circuit-emitted photons from reaching the pixel array. This physical barrier, named "Optical Trench" is a TSV-like structure, crossing the whole epi depth, coated with Aluminum to serve as a light block (Fig 7,8).

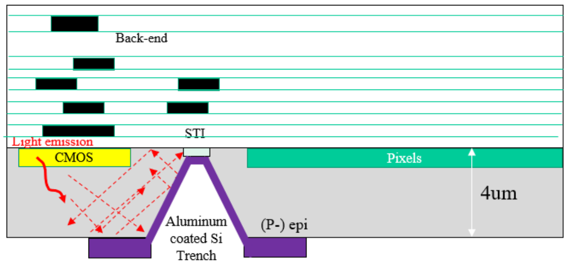

Fig. 7. Schematic drawing of the "Optical Trench", blocking the emitted NIR photons from reaching the pixel array

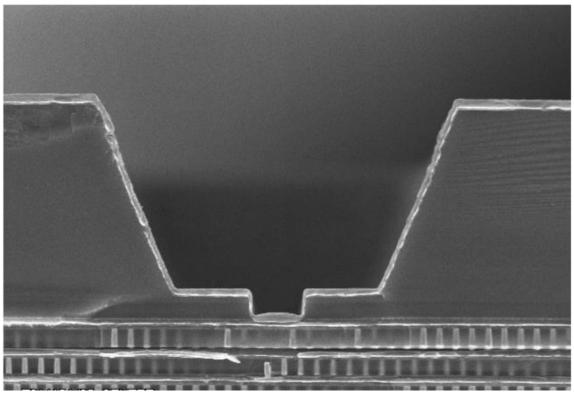

Fig. 8. SEM image of the "Optical Trench" (Pad area)

A sloped Silicon etch process (at the backside of the wafer) was developed to enable high quality metal coating inside the Optical Trench. The metal coating is connected to one of the chip's ground pads, and is separated from the EPI layer using an isolation layer.

Implementing the "Optical Trench" combined with several pixel and circuit design techniques helped solve this effect specifically (Fig 9,10) and achieve an overall Dark Current of 0.02 e/sec at -50ºC, which enables capturing a high-quality image at 300 seconds integration time.

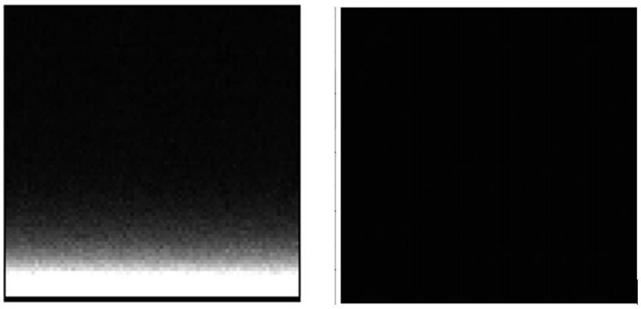

Fig. 9. Comparison of High-Gain Dark Images captured with "Ultrasat Sensor" (a small ROI at the bottom side of the Pixel Array is presented). On the left side – a sensor which was manufactured without the "Optical Trench". The 'glow' at the bottom rows is clearly seen. On the right side – the regular sensor, with "Optical Trench" – the 'glow' is fully eliminated

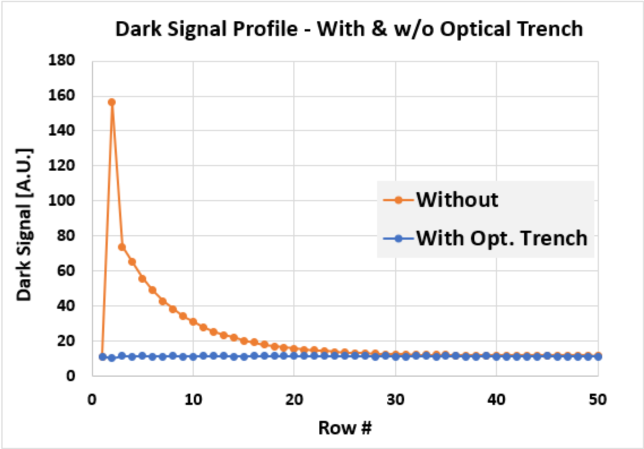

Fig. 10. Dark Signal Profile (of the 2 images shown on Fig.9)

V. SUMMARY

In this paper we presented the main development challenges of the "Ultrasat" pixel and the ways we found to achieve all the design goals. The Pixel performance summary is described below (table 1).

The unique process and device features which were developed here didn't only contribute to the success of the Ultrasat mission, but also defined a path that enables a successful design of many other types of scientific CMOS Image Sensors.

TABLE I. PIXEL PERFORMANCE SUMMARY

Parameter	Ultrasat Sensor		
	Target	***Actual***	***Units***
QE (Avarage at 220-280nm)	>60	80 at 240nm AVG > 60	%
Conversion Gain (High Gain)	>90	>100	uV/e
Full Well Capacity (Low Gain) at 5 Minutes Integration	>140	>150	Ke-
Temporal Noise Floor	<3.5	<2.5*	e-
Dynamic Range	>92	95	dB
Dark Current at -70C	<0.026	0.02 at -50C*	e-/sec/pixel

*Wafer level test. Waiting for accurate data from packaged sensors

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