Voltage domain TDI with diffusion enhanced pixels

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For a space application in "push broom" remote sensing, with very large pixels for visible light and near-infrared detection at dusk, we reached out to a maximum light sensitivity by combining the largest possible pixel pitch, very high fill factor and high conversion gain. To increase the sensitivity further, we introduce a four-stage analog voltage domain TDI.

The device is TID- and SEE-hard. It is manufactured in XFAB's XS180nm CIS process. We present measured results on photoresponse, the speed of photocharge collection, the effect of TDI on read noise, and dynamic range.

1. VOLTAGE DOMAIN TDI

"Emulation" of TDI operation in CMOS, in analog voltage domain, in on-chip digital or off-chip digital domain has been proposed multiple times in the past [7-10]. On-chip emulation suffers from the circuit overhead which is typically much larger than the mere pixel size. The second drawback of analog or digital emulation is that the total (after TDI) read noise increases with the square root of the number of TDI stages. However, Photon Shot Noise (PSN) grows as the square root of the number of TDI stages as well, for both "charge domain" and "emulated" TDI. Thus, in operation points where PSN dominates, TDI emulation can have equivalent performance as charge domain TDI.
The present analog domain TDI image sensor [11] has 4 linear arrays of 143µm pixel pitch, 4-stage TDI cells, as in Figure 1. TDI operation is realized by analog summation of 4 time-delayed samples of 4 rows of pixels, as in Figure 2.

2. DIFFUSION SPEED ENHANCEMENT

As the pixel is large (143 µm), there is a concern that photocharge should be collected and readout over a transfer gate, in a time span that is insignificant compared to the frame time, 140µs. For such a large pinned photodiode (PPD) pixel a major limit is the diffusion time through the n-implanted region.

The solution presented is based on the creation of a potential valley along the "sun rays" [5, 6, 11]. A moderate electric field of up to 10mV/µm is created in these sunrays [Figure *3*], which enhance collection of electrons towards the center of the pixel. Collection of photoelectrons from the volume of the photodiode to the sunrays is by diffusion, over a shorter distance than in the overall pixel.
By extrapolation of the model and measurements in [6], the total collection time was predicted to improve from about 20µs to less than 5µs.

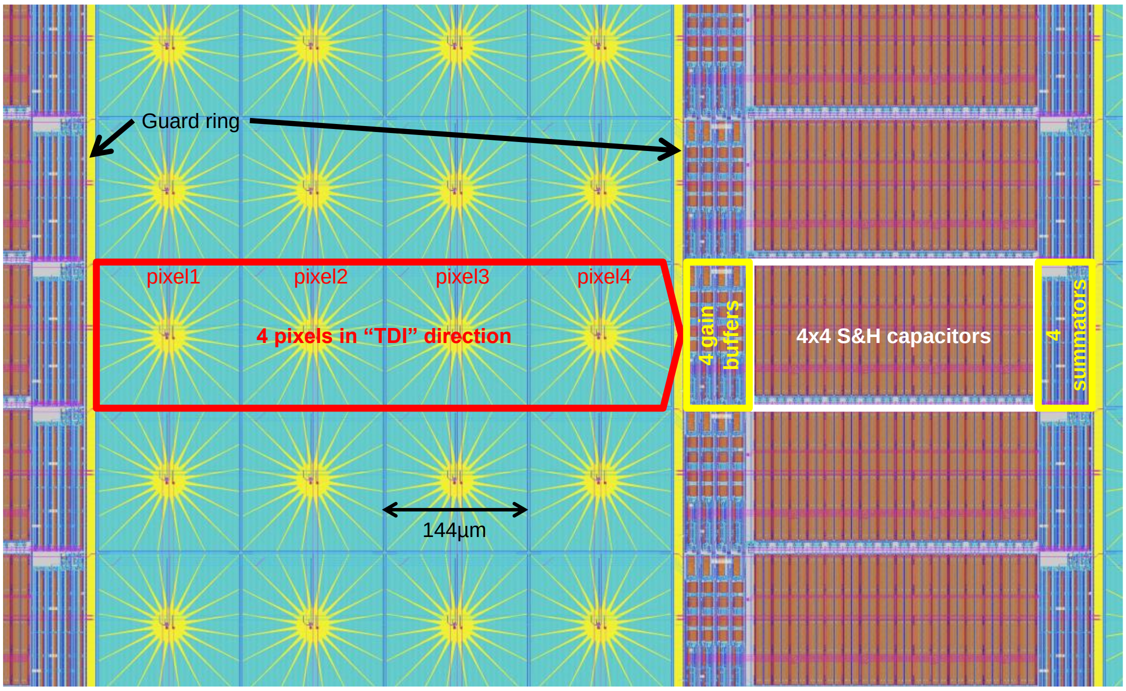

Figure 1 layout detail of the image sensor, showing a "TDI" section. Only representative layers shown for clarity. Yellow: pinned diode, green: P+ implant, blue: metal1, red: polysilicon.

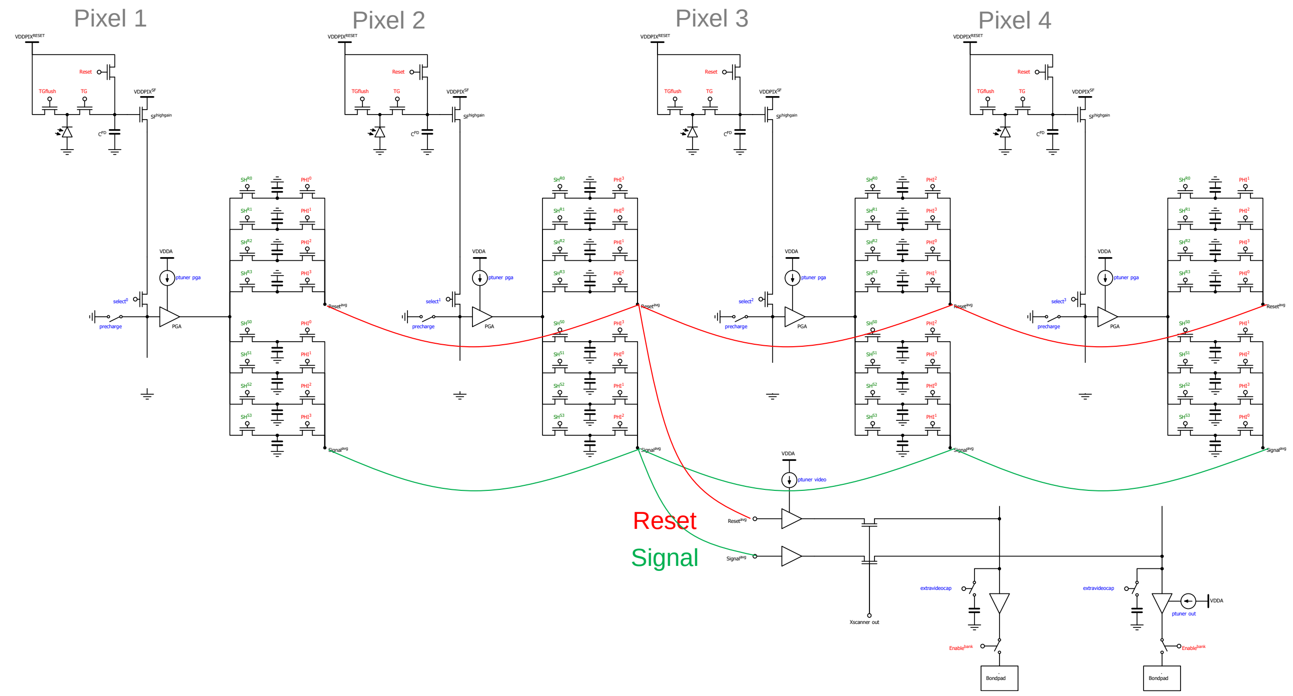

Figure 2 schematic circuit of a single row of 4 pixels in a TDI configuration. At the top: 4 pixels. In the middle: 2x4 Sample and hold stages for each pixel. Bottom: final summation of the four same-position samples.

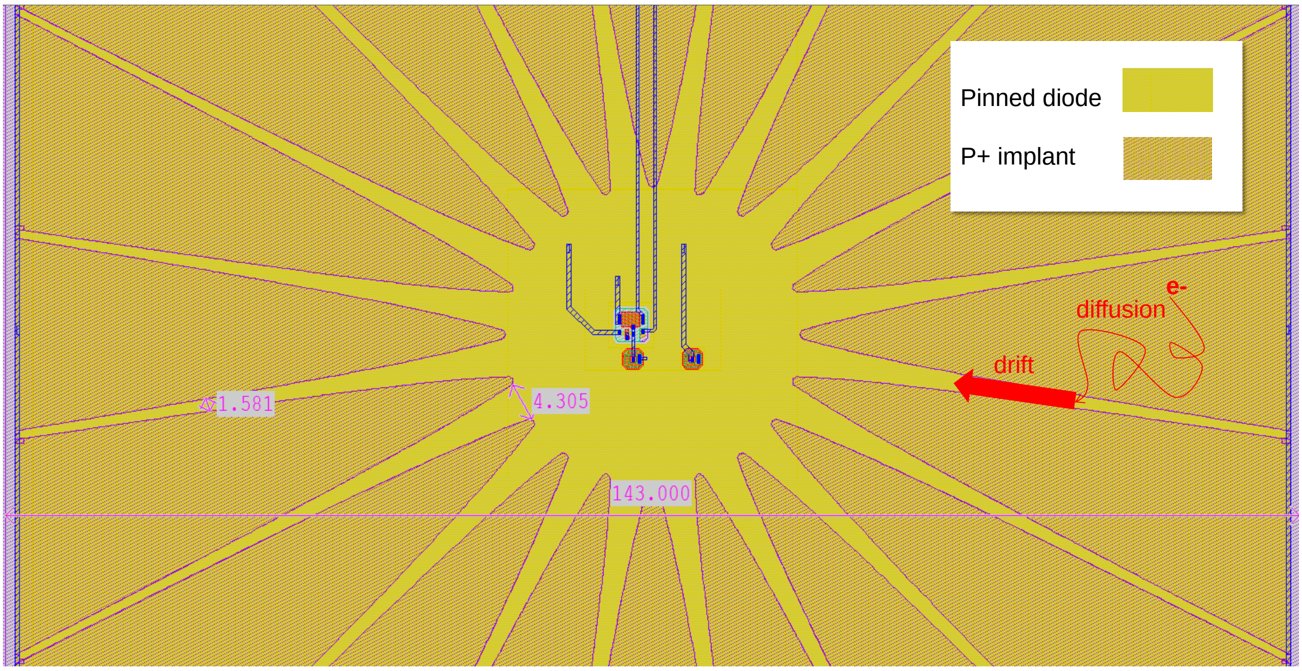

Figure 3 layout of the center part of an individual “HG” pixel. Pinned diode and P+ implanted area shown. Charge will diffuse towards a “sun ray”, and from there on drift towards the center of the pixel.

3. MEASUREMENT RESULTS

Effect of the sun ray pixel shape on QE

One suspected the P+ implanted area to have lower QE than the original PPD area. The effect is found to be minor. The array contains 4 flavors of this pixel, with various coverage ratios of the P+ implanted area over total pixel area. The “HG” pixel of Figure *3* has 85% P+ coverage; the “LG” pixel has no P+. The QE normalized to no metal coverage shows no significant difference in QE.

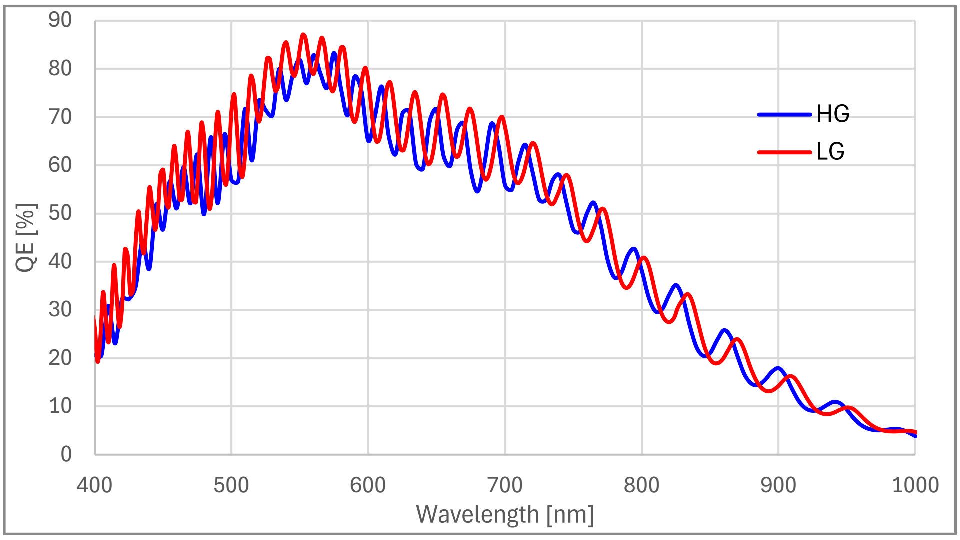

Figure 4 QE divided by metal fill factor, for a high P+ coverage pixel (HG) and a low P+ coverage pixel (LG)

Effect of the sun ray pixel shape on collection efficiency and image lag

The sun ray shape was introduced to enhance charge collection and thus improve image lag. Results will be presented at the conference.

Effect of TDI on noise and SNR

Measured results will be presented at the conference. The following are the predictions.

Table 1 noise and signal to noise ratio (SNR) with and without the voltage domain TDI operation (predicted).

	No TDI	**with 4 stage TDI**	**units**
Maximum signal (Q_{FW})	6000	6000	e-
Dark read noise*	2.71	1.48	$e-_{RMS}$
Minimum expected Signal	24	24	e-
Total noise @ minimum signal	5.60	2.86	$e-_{RMS}$
SNR @ minimum signal	4.31	8.43	

* Dark read noise includes all noise sources except PSN

The noise and signal to noise performance is estimated for the full circuit. At the minimum expected flux, the 4-stage TDI operation almost doubles the SNR [Table 1]. At this operation point PSN is the dominant noise source and defines the overall SNR. Also, the 2nd, 3rd and 4^{rth} ranked noise sources benefit as the square root from TDI operation [Figure 5].

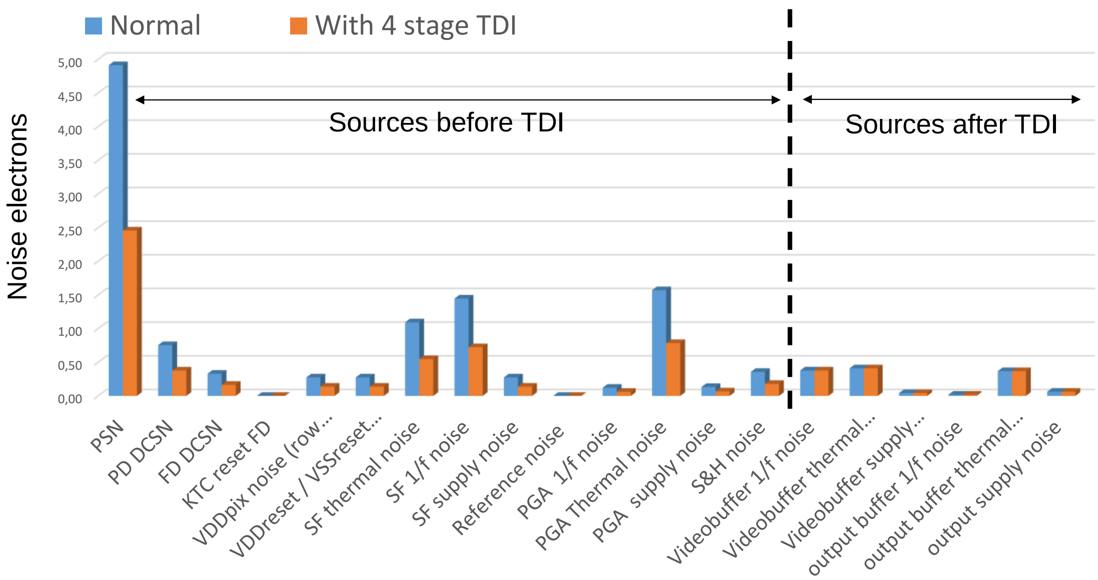

Figure 5 breakdown of noise sources with and without TDI operation

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