A Variable Dynamic Range Single-Photon Imager Designed for Multi-Radiation Tolerance

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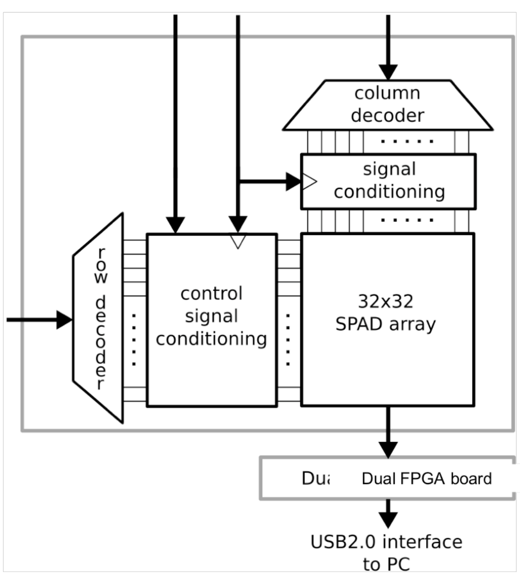
Abstract

We present new measurements conducted on a single-photon imager implemented in CMOS technology. The sensor was designed to sustain massive doses of Gamma irradiation, X-rays, and proton bombardment. The chip was also designed to operate continuously in large magnetic fields without measurable noise and distortion.

The imager consists of an array of 32x32 photon counting pixels with a pitch of 30μm. Each pixel comprises a single-photon avalanche diode (SPAD) based on [1], a 1-bit counter, and miniaturized readout electronics. The chip measures 2.00x2.35mm^2. The block diagram and a photomicrograph of the sensor are shown in Fig. 1. The pixel array is read out in rolling shutter mode via the high-speed row decoder and may be reset after each read operation or read out non-destructively.



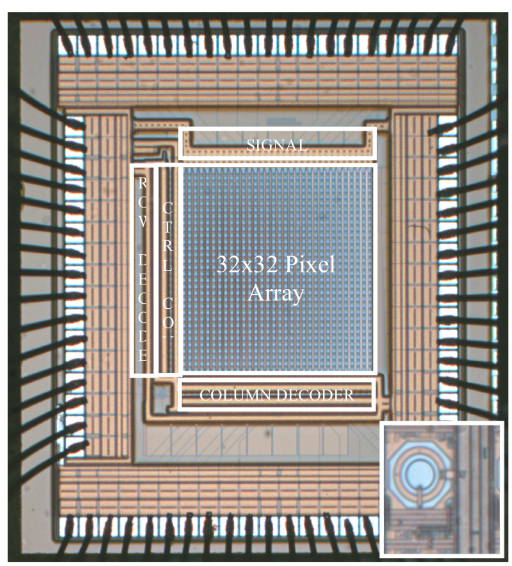


Fig. 1. Block diagram of the sensor (left). Photomicrograph of the sensor system and pixel inset (right).

All 32 columns are read in parallel, thus enabling a complete 1024-pixel frame readout in $T_{\min}$=1.2μs with 1-bit depth. To achieve a higher number of gray levels we accumulate N frames, thus reaching an intensity resolution of $\log_2(N)$ bits at the expense of lower frame rates. The saturation count rate is $1/T_{\min}$, $SNR_{\max}$ for integration time t_{int} is computed as

$$SNR_{\max} = 20\log\left(\frac{t_{\text{int}}}{T_{\min}}\right) - 10\log\left(\frac{t_{\text{int}}}{T_{\min}} + \text{Var}[DC]\right),$$

where the noise power is given by the sum of Poisson noise power and Var[DC], i.e. the variance of the stochastic process underlying dark count generation. The latter is approximated by the average of dark counts during integration, or DCR t_{int}, where DCR is the dark count rate of the detector. In this paper we use median DCR. We believe that this figure is a better representation of the noise performance of the chip as it represents the DCR upper bound for 50% of the pixels.

The intrinsic dynamic range of each pixel is limited from below by DCR and from above by the inverse of dead time. In this design it amounts to 120dB at 1s integration. The dynamic range of the system is programmable by acting upon the speed of the readout. Tab. 1 shows the trade-off between speed and dynamic range in comparison to the maximum achievable dynamic range assuming a dead time of 40ns and negligible DCR. In modern CMOS technologies, high readout speeds may be easily achieved, thus it is often advantageous to reduce the counter depth on-pixel in favor of reduced pitch. In this design, for example, a frame rate comparable to [2]was achieved with 3 bits of counter depth (as opposed to 8 bits), but with 11 times higher pixel density. The pixel density of this design is 8 times higher than that of [3],[4], a 60x48 SPAD array whose pixel comprises two 8-bit counters and a pitch of 85μm.

Frame rate (fps)	Dead time limited dynamic range (dB)	Counter depth limited dynamic range (dB)	System counter depth (bits)
833,333	29	6	1
104,166	47	18	3
3,255	77	48	8
813	89	60	10
25	118	90	15

Tab. 1. Trade-off between frame rate and dynamic range. Reported are dead time limited and counter depth limited dynamic ranges.

The sensor was designed and laid out using techniques to maximize radiation resilience [5]. Details of the pixel and of the design can be found in [6], whereas the chip has now been tested for much larger doses of gamma radiation reaching 300 kGy (30 MRad, Si). To the best of our knowledge, this is the largest dose ever used on a SPAD array and it equals the experiment performed by Fossum et al. [7]. However, in our work the observed noise degradation is negligible if compared to that reported in [7], where dark current increased several orders of magnitude.

The results of the full characterization of the chip are reported in Tab. 2. The radiation testing was performed in four separate measurement campaigns. All measurements from these campaigns were with an excess bias of 2.8 V, unless otherwise noted. The gamma radiation campaigns were performed at ESA-ESTEC in Noordwijk (Netherlands) at the Reactor Institute Delft (RID) in Delft (Netherlands). During the campaign at ESTEC, the sensor received a total dose of 14 kGy (1.4 Mrad, Si) at a dose rate of roughly 4 mGy / sec. During the second campaign at RID, the sensor received a total dose of 300 kGy (30 Mrad, Si) at a dose rate of approximately 800 mGy / sec.

In the third experiment, the sensor was exposed to two separate proton beams at a constant energy of 11MeV and 60MeV, respectively. The experiment was performed at the Paul Scherrer Institute in Villigen (Switzerland).

In the fourth experiment, the chip was exposed to a massive X-ray dose at the University Institute for Radiation Physics in Lausanne (Switzerland). The X-ray beam, generated by a Bipolar Metal-Ceramic tube Comet-Yxlon TU 320-D03, achieved fluence and total dose levels reported in the table, that also lists the results of the DCR change. Preliminary irradiations were performed without any filtering and using a large collimation (27 mm). A series of irradiations at 15kV, 120kV and 200kV showed negligible impact on DCR, PDP, and afterpulsing.

Irradiation type	Source	Fluence/ Flux	Dose (Si)	Initial DCR	Final DCR	DCR after Annealing (anneal time, temp)
Gamma	Co60	41.6 mGy/s	14 kGy	153	13487	276 (172 h, 80° C)
		797.5 mGy/s	300 kGy	128	N/A	25877 (1500 h, 20° C)
X *	Comet-Yxlon TU320-D03	4.3 AsV^2	0.25 mGy	204	N/A	204 (1 min, 20° C)
		324 AsV^2	0.25 mGy	204	N/A	204 (1 min, 20° C)
		900 AsV^2	0.5 mGy	204	N/A	204 (1 min, 20° C)
Proton	Accelerator	$1.8 \times 10^7 p/cm^2/s$ (11MeV)	400 Gy	140	6298	3884 (10 d, 20° C)
		$8.3 \times 10^7 p/cm^2/s$ (60 MeV)	400 Gy	142	6290	1299 (21 d, 20° C)

Tab. 2. Irradiation experiment summary. The median DCR is reported in Hz at room temperature. Photon detection and afterpulsing probabilities, and maximum frame rate remained unchanged after all three types of irradiation. The final DCR, when reported, was measured with the sensor still being irradiated. *Note: X-ray measurements were performed with an excess bias of 3.3 V rather than 2.8 V.

References

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