ALPHACORE

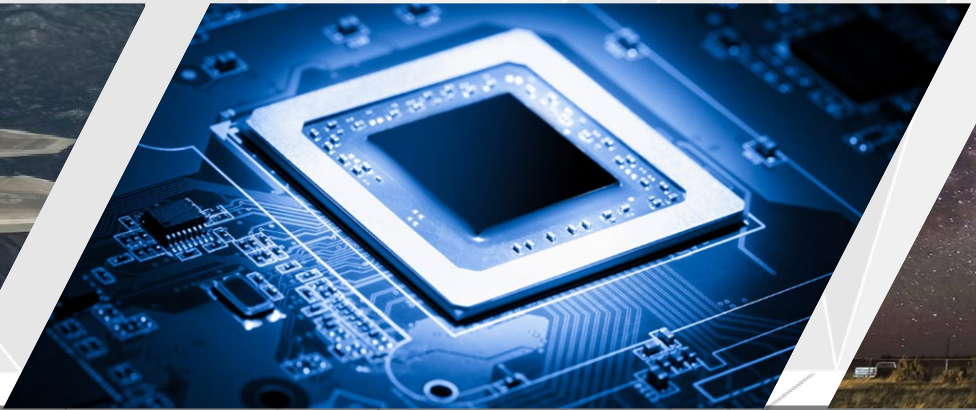
ROBUST HIGH-PERFORMANCE MICROELECTRONICS

Radiation-Tolerant High-Speed Camera

Contract # DE-SC0013232

DOE NP SBIR/STTR Exchange Meeting

August 13-14, 2020



Presentation Outline

- Alphacore Overview
- Alphacore’s DOE SBIR Phase II A Program Overview
- Radiation effects on microelectronics
- Alphacore rad-hard sensor and camera
- Future Plans
- Alphacore products and IP

Alphacore Overview

Top Computer Hardware Companies

- Founded in 2012 and located in Tempe, Arizona
- Providing technologies that enable major advances in:
  - Homeland Security
  - Defense
  - Aerospace
  - Scientific Research
  - Medical
- Alphacore has had explosive revenue growth since the beginning and hit significant milestones:
- Ranked in **Inc. 5000'**s list of fastest growing companies **two years in a row:**
  - **#420** in 2018 and **#578** in 2019
- 3-year company growth of **767% since** 2016
- **6th fastest growing computer hardware company** in the country as of 2019.
- Alphacore's office space has grown nearly **20x since July 2016.**

Alphacore Products

Analog/Mixed Signal/RF ICs and IPs

Imaging Solutions

Power Management

Cybersecurity & Reliability Monitoring

Radiation Hardened Electronics

Alphacore's product catalog consists of components and IP for

- **Data Converters** such as analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), with **ultra-high speeds and low power**
- **Imaging systems** such as **high-speed and rad-hard** IR and visible cameras, ROICS, and image sensors
- **Power management components** and interface ICs such as **high-efficiency** RF Power Amplifiers, **high-speed** transceivers, phase-locked loops (PLLs)
- IC Authentication tools with **built-in-self-test (BIST)** capabilities and **Multi-attribute Authentication and Reliability techniques**
- **Radiation Hardened** versions of IP and ICs may be available

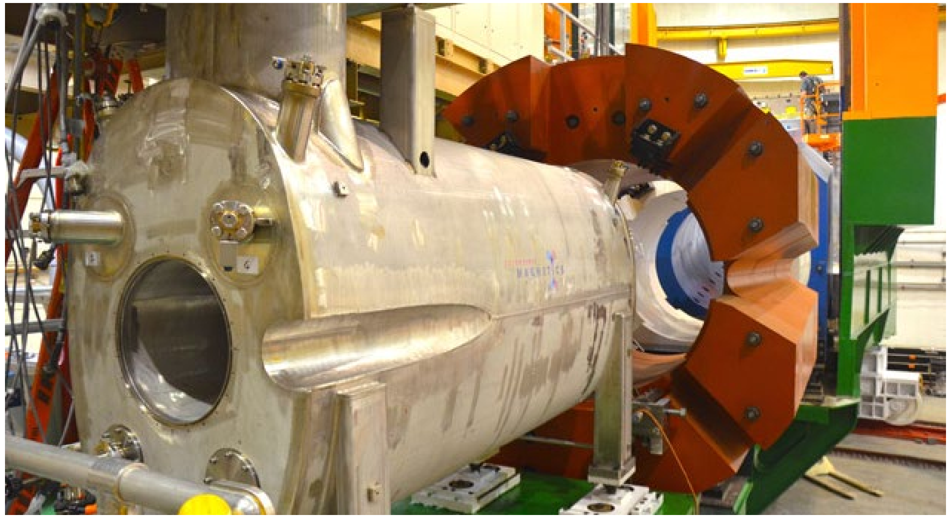
Alpacore DOE Ph II A Program Overview

Program Overview

DOE SBIR Phase II A Contract #DE-SC0013232

DOE need:

A radiation-tolerant, triggerable, **high speed imaging chip and a complete camera system** for investigating rapidly occurring phenomena in radiation environments. The primary applications are beam monitoring and scientific experiments at nuclear physics facilities.



Program Motivation

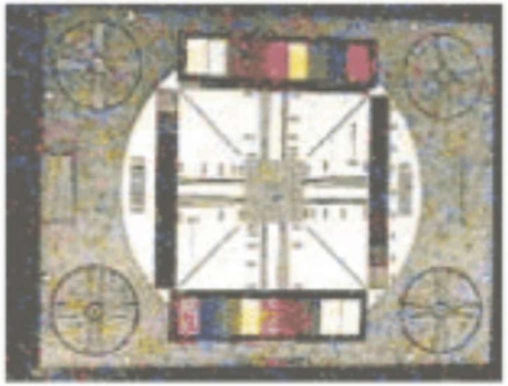
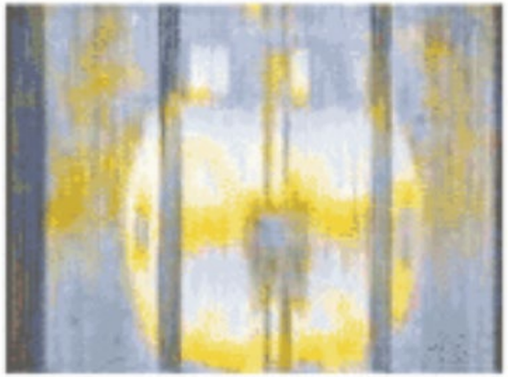


Image before irradiation



…and after 10krad

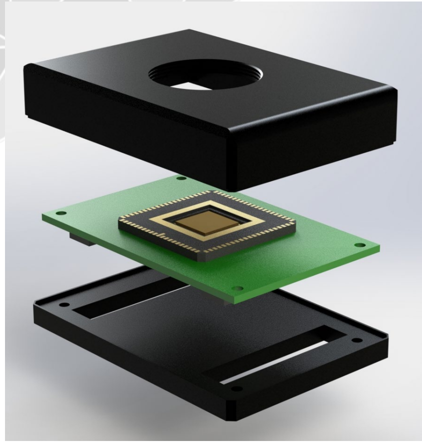
[Courtesy: Vision System Design]

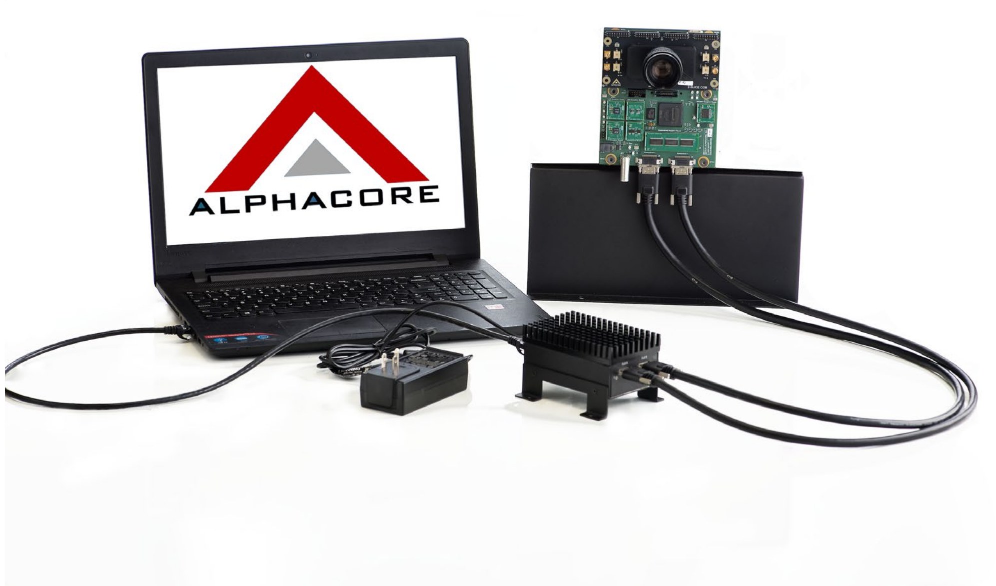
Non-hardened image sensors and cameras typically fail after a few tens of kilorads

Hardened sensors and cameras typically target nuclear plant monitoring applications and have low frame rates (30fps)

High-speed rad-hard image sensors and cameras do not exist (to the best of our knowledge)

Program Goals

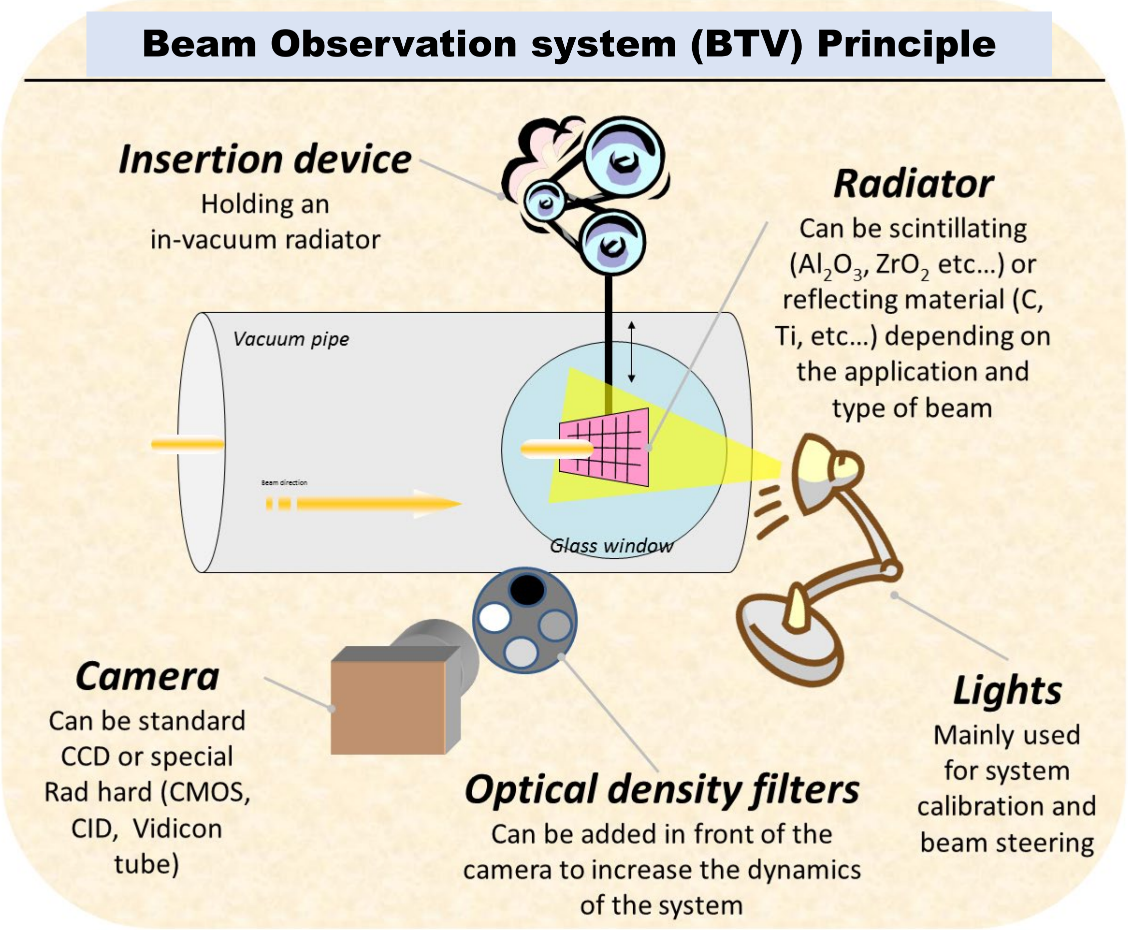


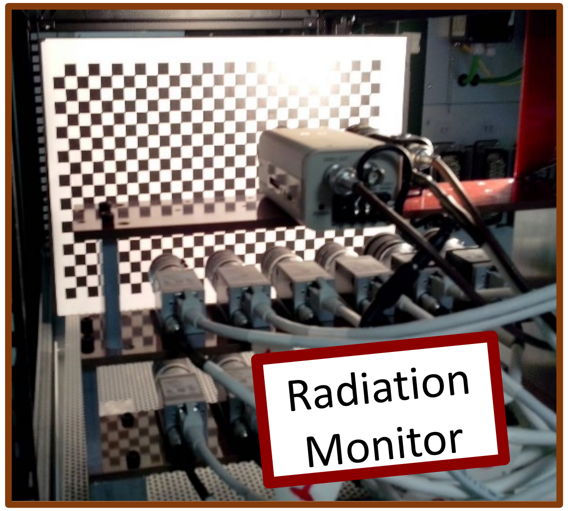


Specification	Description
Resolution	Minimum: 10 kilopixels Objective: 1 Megapixel
Frame rate	Minimum:1 kfps Objective: 10 kfps
ADC resolution	10 bits *Dynamic range increased with a programmable gain amplifier*
Pixel	20 µm x 20 µm pixel size 65% fill factor
TID tolerance	Minimum: 100 krad Objective: 300 krad
SEL	LET_th > 20 MeV*cm^2/mg
DDD	1MeV neutron eq. fluence 1*10^14n/cm^2

Camera Irradiation Tests at CERN

Images from *"Irradiation Test of Commercial Digital Cameras at the CERN CHARM facility"*, Scintillation Screens and Optical Technology for transverse Profile Measurements, ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019 S.Burger – CERN



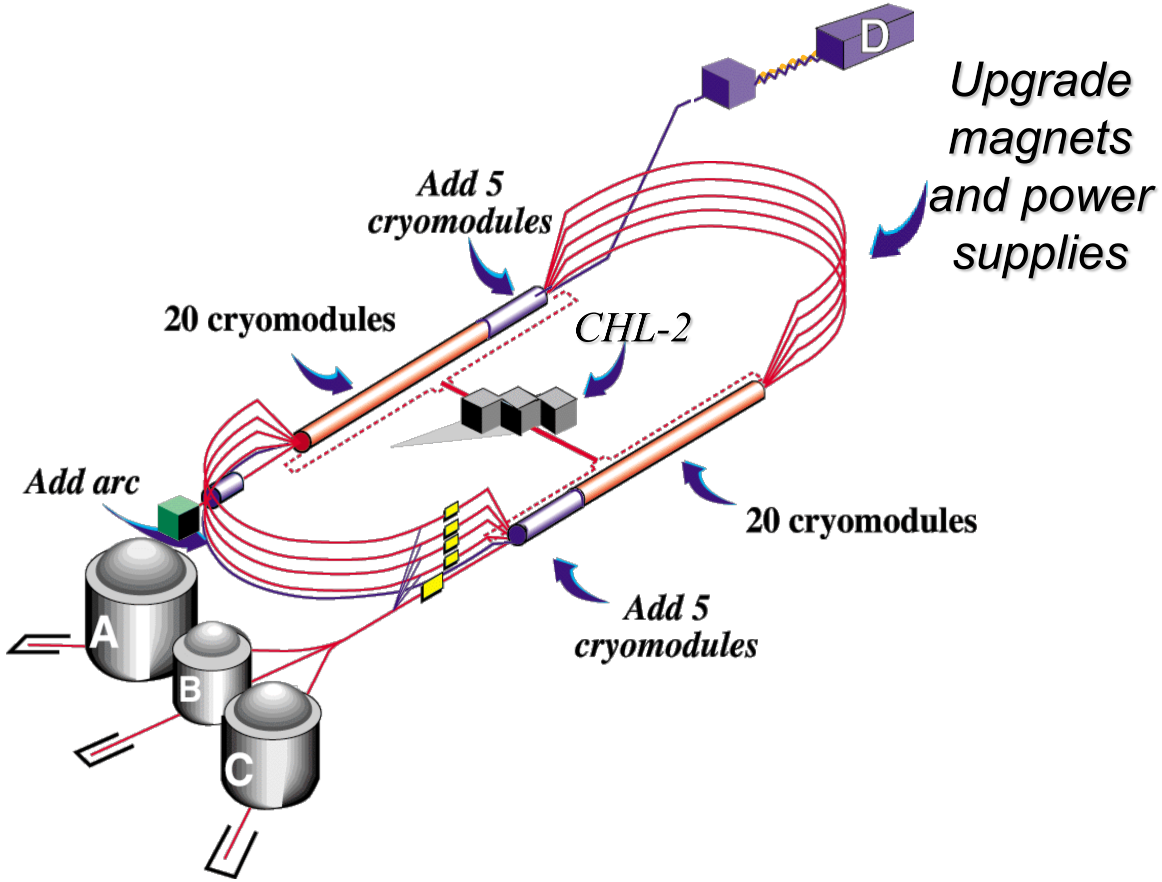


- Arrays of digital cameras tested at CERN
- Camera failures appeared within a few minutes of beam arriving
- TID limit to kill the cameras 116-161 Gy

Images from *"Irradiation Test of Commercial Digital Cameras at the CERN CHARM facility"*, Scintillation Screens and Optical Technology for transverse Profile Measurements, ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019, S.Burger – CERN

Applications to JLAB environment

CEBAF 12 GeV Upgrade



JLAB Continuous Electron Beam Accelerator Facility (CEBAF) has need for rad-hard imaging solutions

Investigating change in beam size for different helicity states

Demands high frame rate

JLAB beam monitoring environment expected to be characterized by photons, and neutrons

Synchrotron radiation in the radiation arcs

Photons and neutrons from beam losses in the linacs

Off the shelf cameras have been tried in the same location being targeted

image sensor is what fails with what appear to be pixels that are always full on

Assess electronics for photon induced effects (TID) and neutron induced effects (DDD,SEEs)

COTS components tested at JLAB in Phase II A failed at 13krad

Images from *"Jefferson Lab Scintillating Screens"*, ARIES-ADA Topical Workshop, Krakow, Poland, April 1 to 3, 2019, Kevin Jordan

Phase II A Status

- 1024 x 786, 10 kfps taped out in 180nm CMOS CIS process
- Camera electronics prototype designed and fabricated
- Custom FPGA firmware developed for sensor frame capture and transfer to PC via camera link
- Software developed for receiving and analyzing frames at the PC
- Tested COTS electronics in environment at JLAB
- Database of radiation tested COTS supporting sensor electronics for full radiation tolerant camera solution
- Tested sensor prototype in Co60 gamma radiation chamber
- Testing stopped at ~150krad with no measurable effects
- Expected tolerance is beyond 300krad, possibly in the low Mrads
- Subcircuit testing 100% functional for;
  - Phase Locked Loop
  - Digital controls
  - Serial interface
  - Serial data readout digital registers
  - Scalable Low Voltage Signaling (SLVS) transceivers

Radiation Effects on Microelectronics

Radiation Effects on Electronics (1)

Radiation effects on electronic devices are commonly divided into 2 effects:

1. **Cumulative effects:**

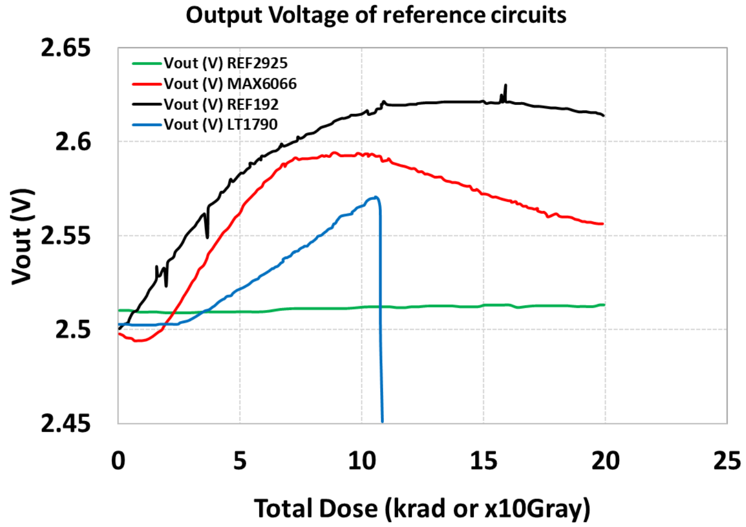
- Appear as a parametric variation of electrical parameter/characteristic leading to functional error
- Exple: I_{in} of OpAmps, V_{ref} of LDO or reference, bit error in NVM memory, I_{cc} of Integrated circuits, dark current of pixels

Total ionizing dose (TID): due to ionization induced by photons, electrons, protons

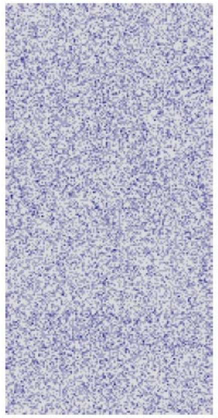
⇒ impacts CMOS and bipolar technology, optic fibers

Displacement damage dose (DDD): due to displacement effects from protons and neutrons

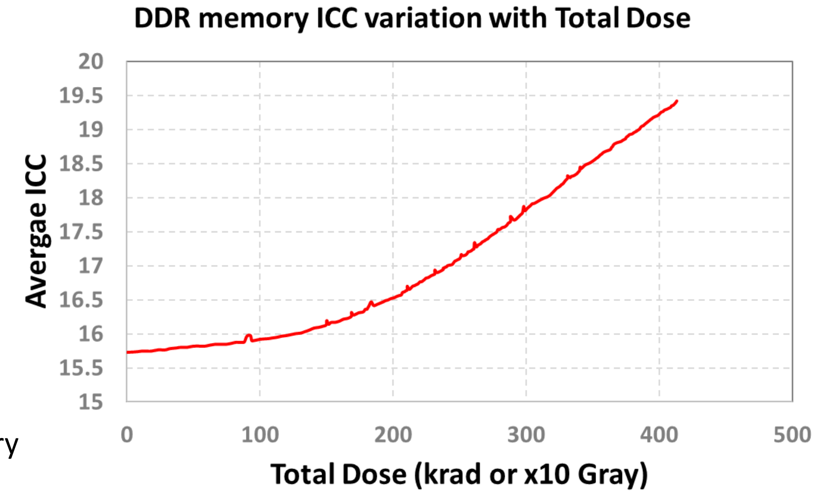
⇒ impacts CMOS, bipolar, optoelectronics, pixels, optic fibers



Data from D. Hiemstra et al, NSREC REDW2018



Error map on a DRAM memory due to TID



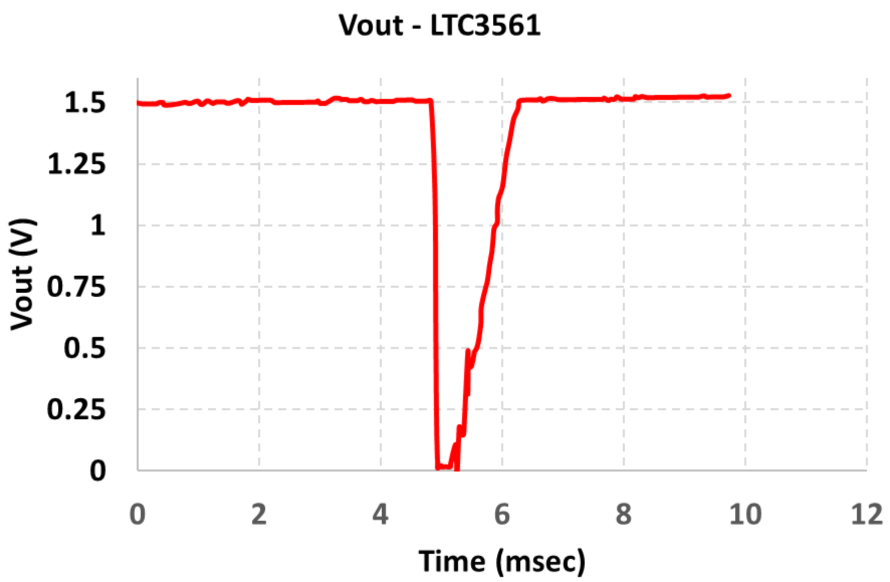
Data from European Space Agency

Radiation Effects on Electronics (2)

Radiation effects on electronic devices are commonly divided into 2 effects:

2. <u>Single event effects (SEEs)</u>:

- *Can be destructive (SEL, SEB, SEGR) and non-destructive (SET, SEU, MBU, SEFI).*
- Appear as digital bit flip, transient signal in the case of non-destructive effects or functional error of digital circuits
- Destructive effects can occur with neutron

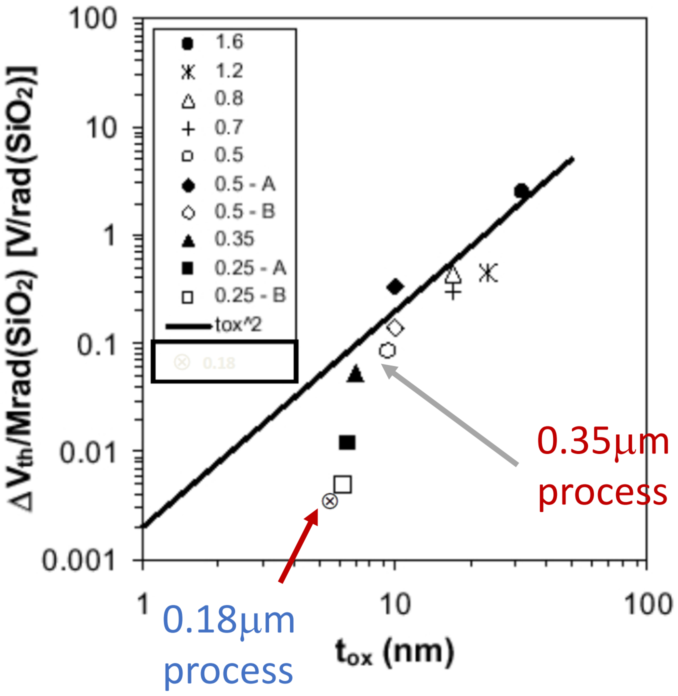


Neutron induced transient on a LT3561 Synchronous Step-Down DC/DC Converter
From T. Fairbanks et al, NSREC REDW 2018

Effects mostly studied for heavy ions induced SEEs for space applications

Neutrons affect electronics through generation of ions after nuclear interaction with atoms present in the materials

Radiation Tolerance vs. Process Node



Radiation tolerance obeys a t_{ox}^2 law

➔ 0.18mm process “naturally” more radiation tolerant than 0.35mm process

From 0.25mm down, tunneling effect kicks in (departure from the t_{ox}^2 law) and further help the smaller node process radiation tolerance

Process used for this design has two types of transistors:

- Core transistors
  - Used almost everywhere (~90% of the transistor population)
  - 0.18mm process
  - Power supply of max 1.8V
- I/O transistors
  - Used where >1.8V supply is needed (pixel, column…)
  - 0.35u process
  - Power supply of max 3.3V

Oxide thickness (t_{ox}) is ~2% of the process node:

~8nm for 0,35mm process and ~4nm for 0.18mm process

Radiation tolerance depends directly upon t_{ox}

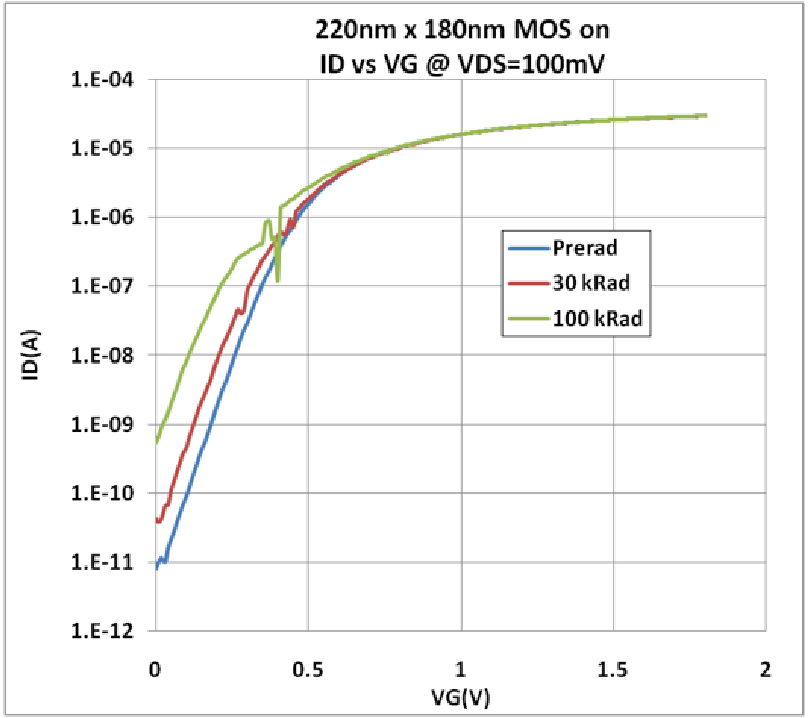
Strategy:

Special attention (layout) must be paid for I/O transistors

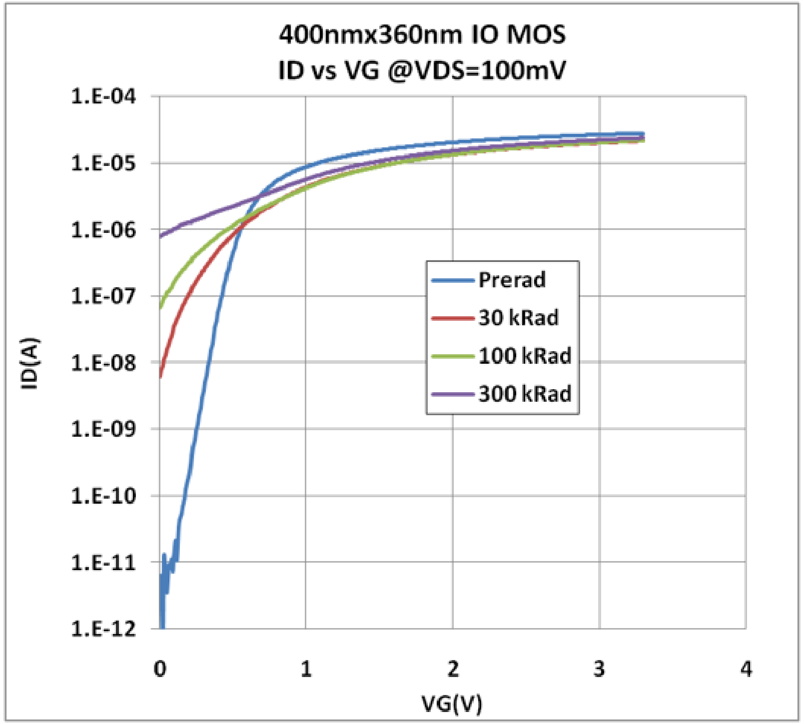
Provision (schematic) must be made for core transistors

180nm CMOS 1.8V vs. 3.3V NMOS Leakage

Based on Co-60 tests, the thick oxide NMOS has 100X higher leakage than the core NMOS => Design with 1.8V core transistors



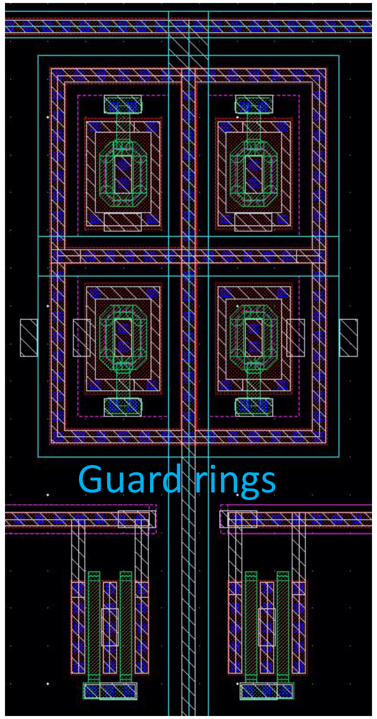
Min. size 1.8V core NMOS



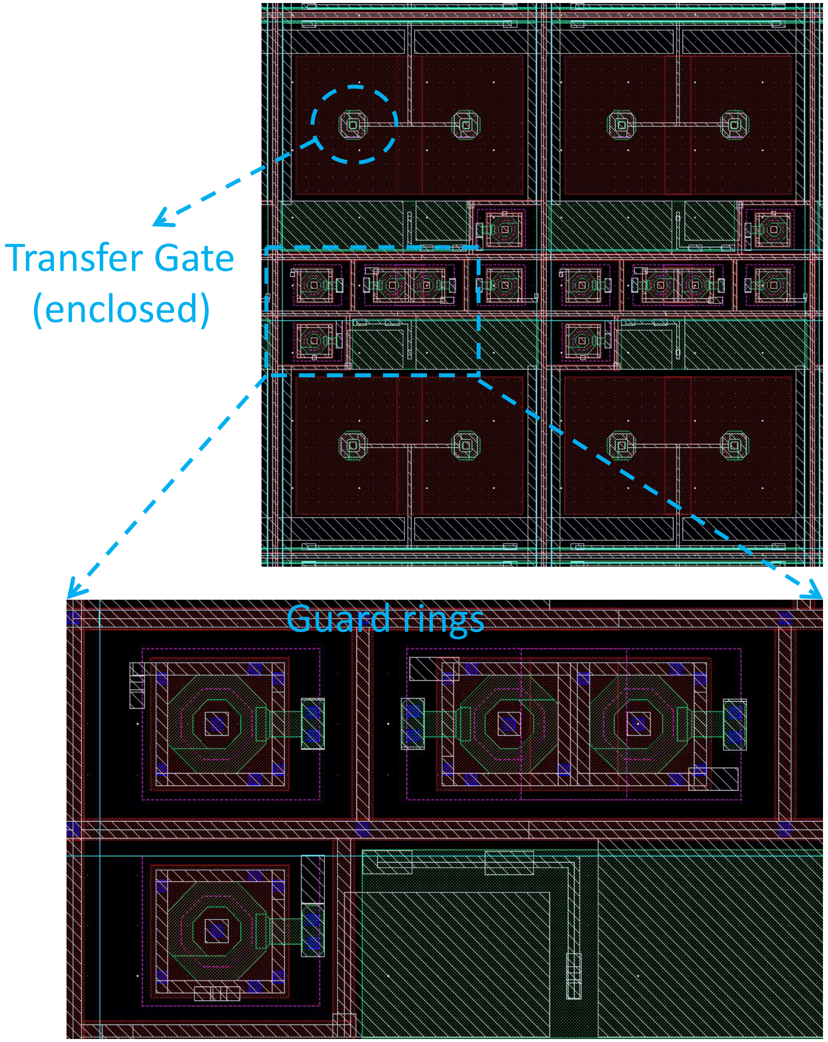
Min. size 3.3V IO NMOS

Rad-Hard PPD Pixel Layout

Column Layout



Pixel Layout



Rad-Hard by Design and Layout techniques

- Enclosed NMOS transistor
  - Avoid STI leakage path
- Guard rings
  - Prevent leakage between transistors

- Annular NMOS devices used for pixel transistors
- Pinned Photodiodes (PPD) offer inherent conversion gain (40µV/e-) ideal for low light, high speed application
- 20µm by 20µm pixel
- Annular transfer gate on the PPD reduces STI and increases radiation tolerance
- Fill factor of 60-65%
- Very fast transfer time of 170 ns or better

Implications for Camera Electronics

Camera system includes:

- Digital electronics: FPGA, DRAM memory, Flash memory
- Mixed signal electronics: DACs, LVDS transceiver
- Linear/Analog: voltage /power delivery with DC/DC converter, LDO, Voltage references
- Image sensor IC

All these elements can be susceptible to both TID from high energy photons and DDD/SEEs from neutrons

- Review literature for existing testing data (both TID and SEEs) of candidate part =>create database
- Evaluate possibility of using candidate parts in camera system
- If candidate part/replacement part data not found, conduct dedicated TID testing to assess TID effects on selected parts

The modular camera design (made of daughter board for each elements) enables use and reuse of different parts

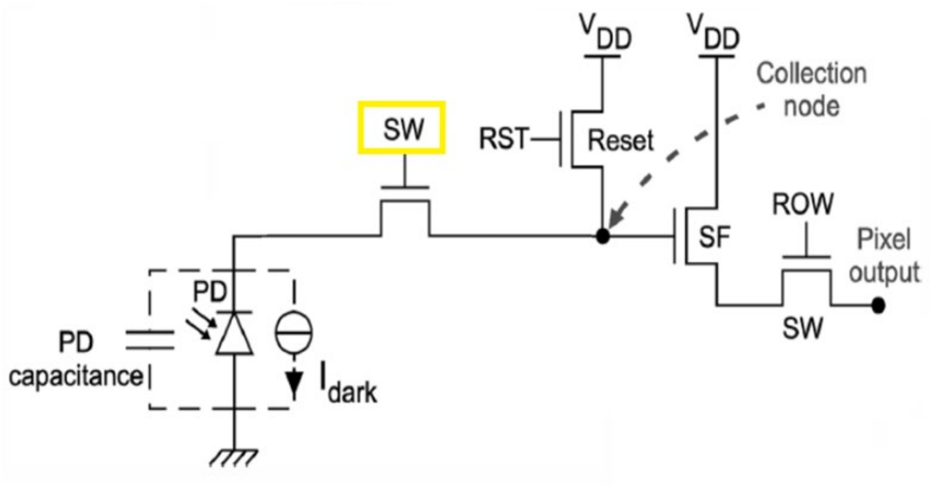
Paper No., Page No.					Data		Total Ionizing Dose, X-ray, P-pions				Single Event Effects, H-heavy ion, P-proton, L-laser, N-neutrons							Displacement Damage		Facilities	Environment
					Terrestrial	Flight	Co60		Protons	Electrons	SEU	SET	SEFI	SEL	SEB	SEGR	Dose Rate	Protons	Neutrons		
3. pp. 15-21	A. Topper	AD620SQ/883B	Operational Amplifier	Analog Devices	√ - 3k-10krad			√ - 10mrad													
		OP484	Operational Amplifier	Analog Devices	√ 50k-75krad			√ - 10 mrad													
		LM193	Voltage Comparator	Texas Instruments	√			√													
		ADCMP600	Voltage Comparator	Analog Devices	√			√													
		ADCMP604	Voltage Comparator	Analog Devices	√			√													
		MT29F4G08ABADAW	Flash Memory - 4Gb	Micron	√>40krad at		√	√													
		HS-4423BEH	FET Driver	Intersil	√			√													
		2N5154U3	NPN BJT	Microsemi	√			√													
		ADF4252	Frequency Synthesizer	Analog Devices	√			√													
		ISL71590	Temperature Sensor	Intersil	√			√													
		OPB847	Optical Switch	Optek	√													√			
		ACPL-785E	Optocoupler	Avago Technologies	√													√			
		TUD69H1B	LED	Sensor Electronics Technology	√													√			
		TUD89H1B	LED	Sensor Electronics Technology	√													√			
		TCE49H1B	LED	Sensor Electronics Technology	√													√			
4. pp. 22-27	S. Danzeca	DG408	Analog Multiplexer	Vishay	√				√												
		DG408	Analog Multiplexer	Intersil	√				√												
		DG408	Analog Multiplexer	Analog Devices	√				√												
		DG408	Analog Multiplexer	Maxim	√				√												
		INA121	Instrumentation Amplifier	Texas Instruments	√				√												
		AD8397ARZ	Operational Amplifier	Analog Devices	√50krad				√												
		AD8031ARZ	Operational Amplifier	Analog Devices	√50krad - SET				√			√P									
		AD8032ARZ	Operational Amplifier	Analog Devices	√50krad				√			√P									
		AD8610ARZ	Operational Amplifier	Analog Devices	√50krad - out of				√												
		MAX7300	I/O Expander	Maxim	√				√			√P									
		MCP23017	I/O Expander	Microchip	√				√												
		CY62167GE30-45ZXI	SRAM	Cypress	√				√			√P									
		CY62147GE30-45ZSXI	SRAM	Cypress	√				√			√P									
		ADUM3401A	Digital Isolator	Analog Devices	√				√			√P									
		ADUM3401B	Digital Isolator	Analog Devices	√				√			√P									
		ADUM3402EP	Digital Isolator	Analog Devices	√				√			√P									
		ADUM3402B	Digital Isolator	Analog Devices	√				√			√P									
		TCL 120-112	Traco Power	AC-DC Converter	√				√												
		TCL 024-105	Traco Power	AC-DC Converter	√				√			√P									
		TBLC 25-105	Traco Power	AC-DC Converter	√				√			√P									
		ML15	Pulse	AC-DC Converter	√				√												
		DRB50-5-1	TDK	AC-DC Converter	√				√												
5. pp. 28-38	A. Bozovich	2N2907A	PNP BJT	Semicoa	√			√													
		2N2857	NPN BJT	Semicoa	√			√													
		IS-139ASEH	Voltage Comparator	Renesas=Intersil	√			√													
		HS-508BEH	Analog Multiplexer	Renesas	√			√													
		ISL71590SEH	Temperature Sensor	Renesas	√			√													
		HS-117EH	Voltage Regulator	Renesas=Intersil	√			√													
		HS-303AEH	Analog Switch	Renesas	√			√													
		ISL74422BRH	MOSFET Driver	Renesas	√			√													

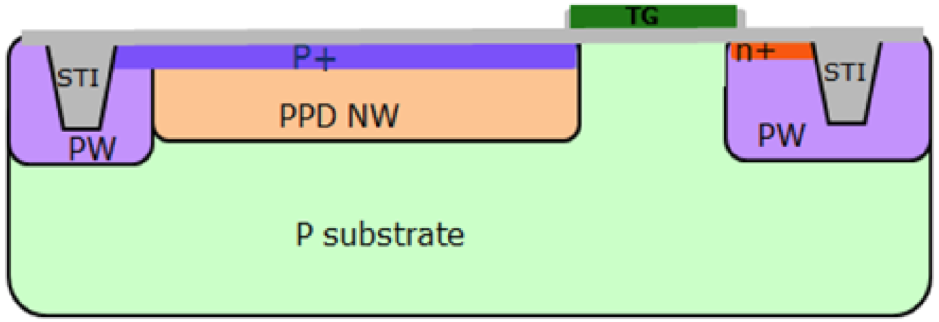
Alphacore image sensor has been designed using RHBD techniques to be TID and SEEs resilient

Need to assess effects on supporting camera electronics and conduct part selection for final implementation

Alphacore Rad-Hard Sensor and Camera

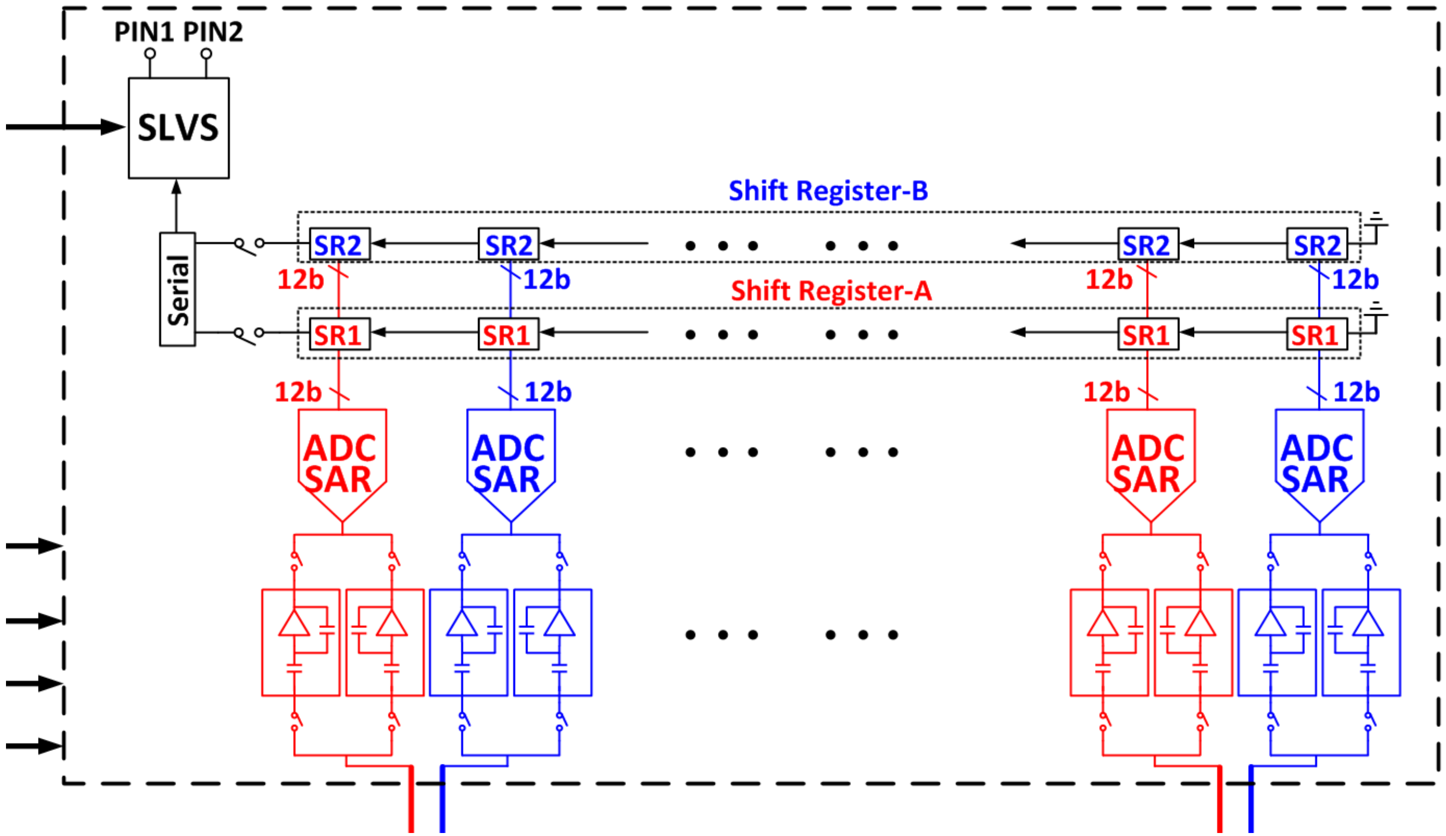
4T Pixel Topology





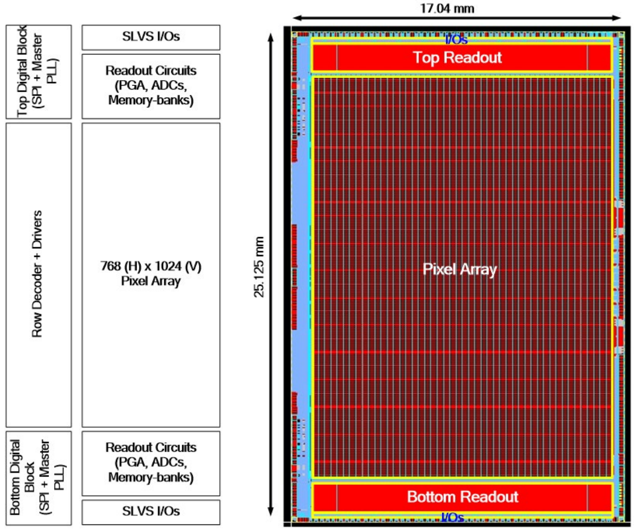
- 1 Megapixel sensor uses 4T pixel topology, Pinned Photodiode (PPD) light-sensitive element
- The pinned photodiode structure uses a shallow p+ layer on top of an n-well layer of a traditional pn junction photodiode. The n well is “sandwiched” between the p+ layer on top and the p epi layer underneath
- A transfer gate is shown as an additional switch (SW), and the collection node is an n+ in p-well floating diffusion
- The PPD is ideal for low light or high-speed applications, such as this DOE program
- Advantages of the PPD and 4T pixel include inherent noiseless gain from PD to the floating diffusion, fast integration and readout times, reduced dark current, lower noise, and increased quantum efficiency

Pipelined PGA, ADC, Readout

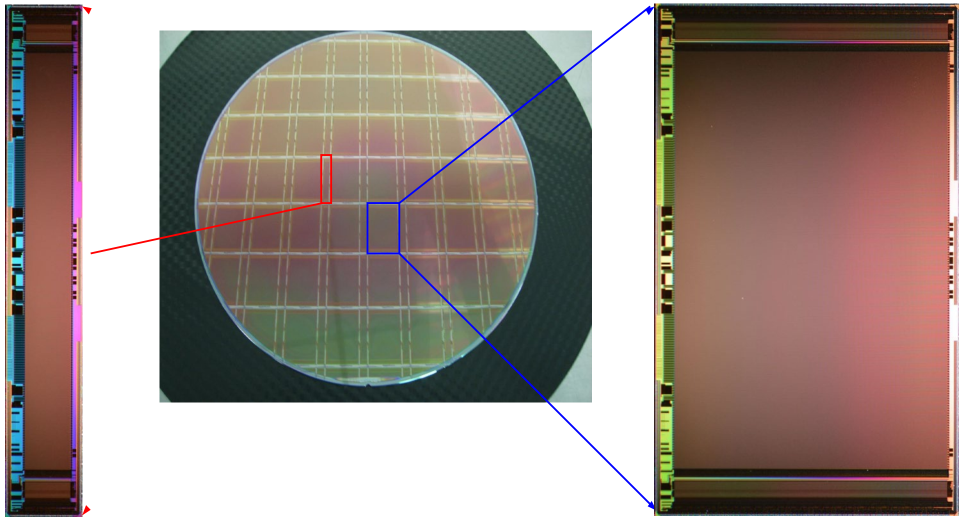


- 2 PGA sample-and-holds per ADC, plus 4 ADCs per column (two top, two bottom)
- Allows pipelined sampling, conversion, and readout.

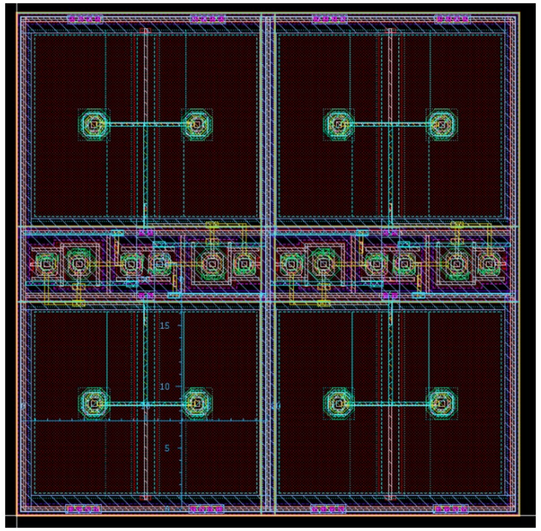
Radiation Tolerance Strategy: I/O Transistors



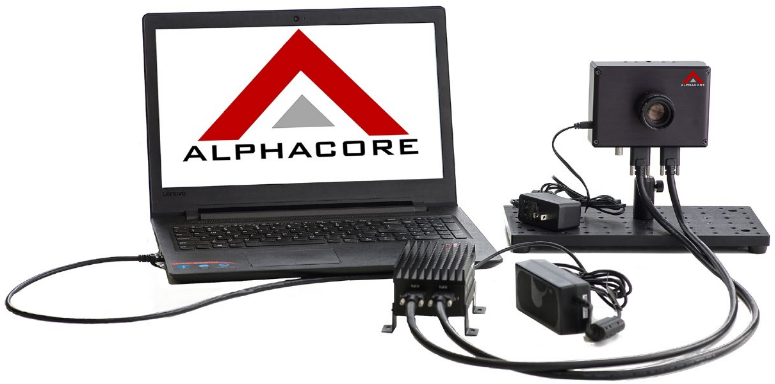
10kfps CIS Block Diagram



128 x 1024 Test Imager, 200 mm Wafer, and 768 x 1024 Full Imager



Annular 3.3V Rad-Hard Pixels



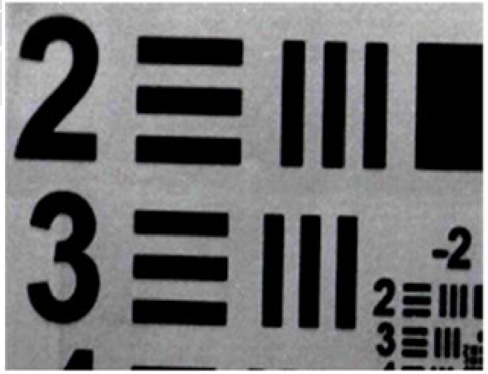
Rad-Hard Camera and System

Testing in Co60 GammaCell Chamber

- 768x1024 pixel resolution
- 10 kfps at full resolution
- Visible wavelengths
- Rolling Shutter
- Monochrome
- Windowed readout, programmable through on-chip rad-hard digital SPI and Control Block
- 4T Pinned Photodiode with Noiseless Gain through Charge Transfer Gate
- Applications include Nuclear Power, Nuclear Physics, Space Imaging, and Medical Diagnostics

ALPHACORE

High Sped Camera Radiation Test

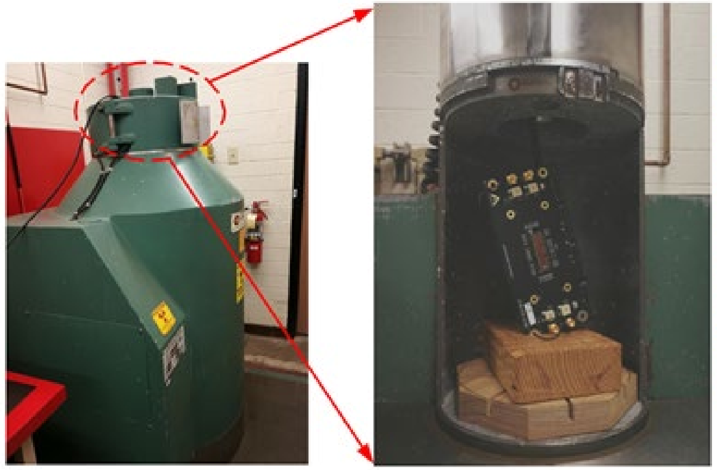


a)

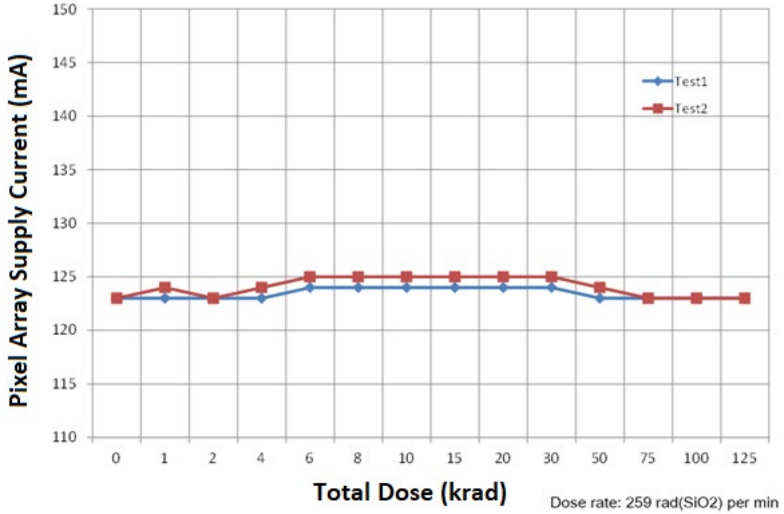
b)

Radiation hardness of high-frame rate commercial cameras is very poor

- **Figure a)** shows an image taken with a commercial high-speed camera at 0 krad(Si)
- **Figure b)** shows an image from the same camera after 3.2 krad(Si)[1]
- The radiation test shows image degradation already at 900 rads
- Clearly demonstrates that non-hardened cameras suffer severe effects even at low radiation doses
- Custom-hardened cameras are thus needed for imaging in radiation environments



c)



d)

Alphacore's Alpha10k Rad-Hard Image Sensor and Camera

- **Figure c)** shows Alphacore's Alpha10k rad-hard image sensor prototype in the ASU Gammacell Co60 radiation test chamber
- **Figure d)** shows no change in baseline pixel array current due to leakage during testing to 125 krad TID
- Alphacore's team has the extensive knowledge of radiation effects and rad-hard by design techniques needed to make space-based camera programs successful including three PhD senior engineers/researchers specializing in the radiation effects area with over 300 related publications
- Alphcore's team also includes electronics experts with >60 years of combined experience in image sensor and camera development.

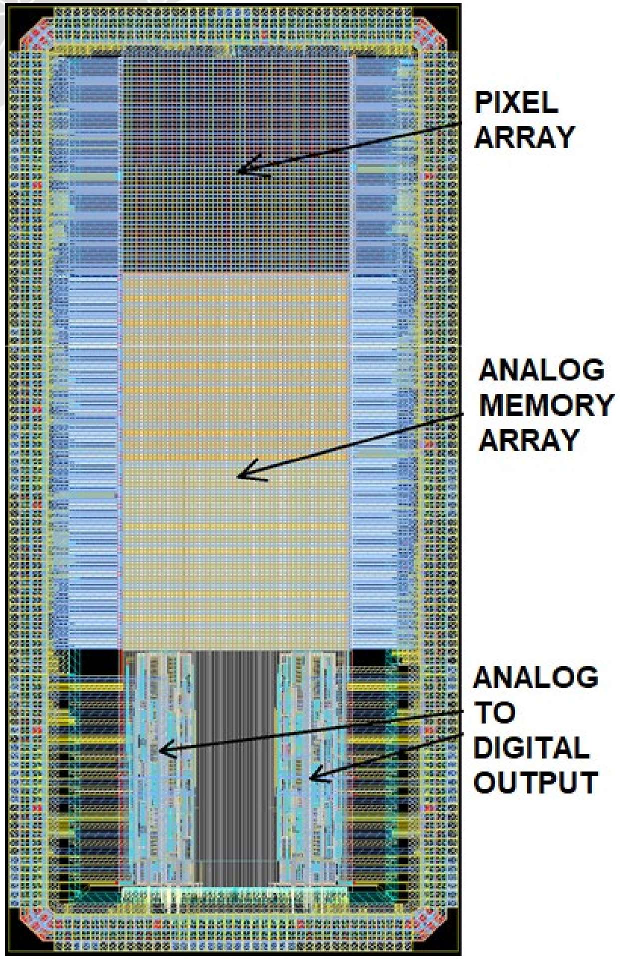
[1] Alphacore's radiation effect engineers recently performed this Co-60 test on a commercially available 500fps camera.

Future Plans

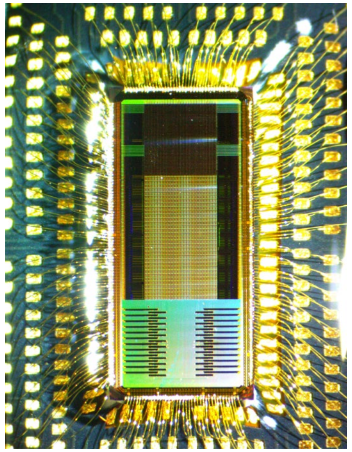
- Radiation-hardened camera boards
  - Identify tested components
  - Use qualified components where possible
  - Test components where required
- Sensor prototype revision with DFM and DFT improvements
- Further TID tests for the standalone image sensor
- Second field test at Jefferson Lab
- Review of TID data for candidate parts (in progress)
- Review of neutron data available on candidate parts
- Conduct TID tests
- Assess need for neutron test
- Evaluate local shielding possibilities
- Ion beam testing of SPI and digital control block at LBNL for SEL and SEU. Digital block uses register space with triple mode redundancy.

Alphacore Products and IP

Alpha 200kfps Prototype



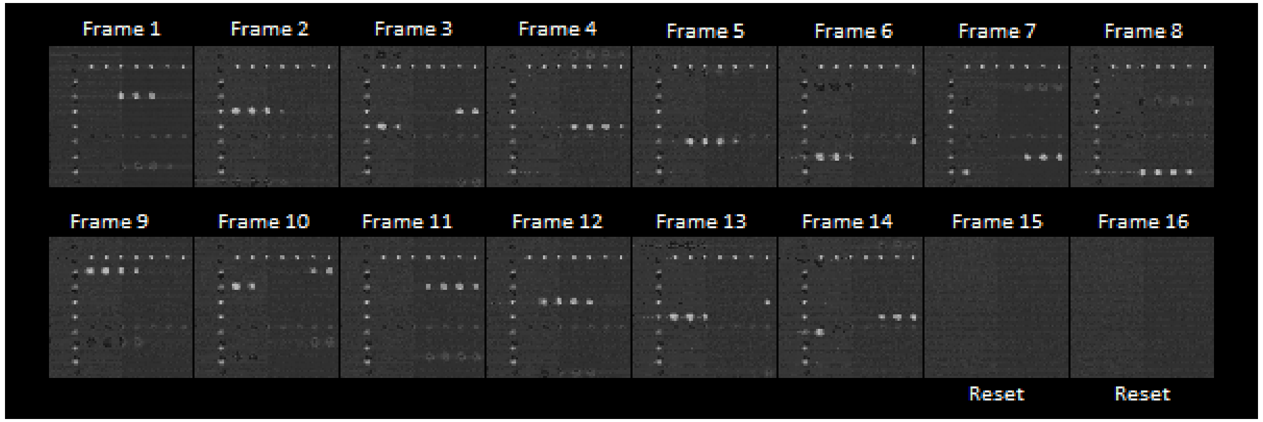
GHOST IMAGE SENSOR



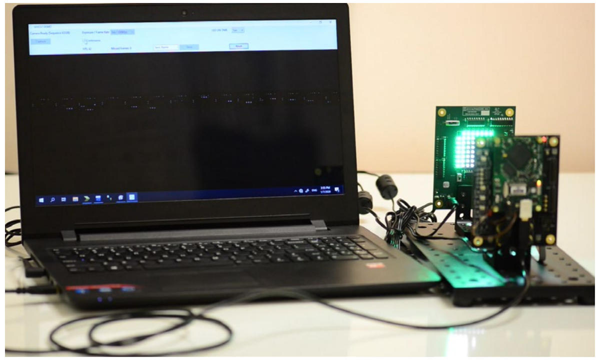
Bonded Image Sensor

200kfps Camera Prototype and Test Target

- 200kfps 16 frame burst
- Prototype developed for AF arena testing object tracking application
- Visible Wavelength
- 16 frame burst mode
- Global Shutter
- Monochrome
- In-Pixel Correlated Double Sampling
- Expandable to 1Mpixel



LED exposure test 1 - 3us exposure at 200kfps, LED frequency 1MHz



LED Array Test Target

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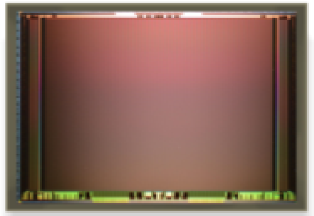
Alphacore Image Sensor Eval Kits

Imaging Solutions

ALPHA 10K

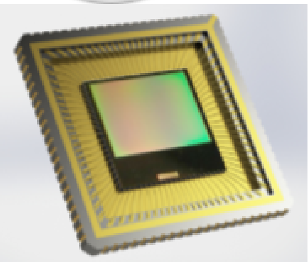


The Alpha10K-RH is a radiation-tolerant, triggerable, high-speed visible light camera, designed to investigate rapidly occurring phenomena in harsh radiation environments. It uses Alphacore's custom-designed CMOS image sensor.

Key features

- 768x1024 pixel resolution
- 10 kfps at full resolution
- 300krad (Si) TID tolerance
- Camera Link medium and full configurations

ALPHA 200K



The Alpha200K is an ultra-high frame rate, burst mode, visible light camera. It uses a 15 µm, 4T pinned photodiode (PPD) light-sensitive element, that makes it ideal for low light and high speed applications.

Key features

- 200 kfps at 100x100 resolution
- Expandable up to 640x480 resolution
- Global shutter, burst mode
- USB interface
- Low Noise

EVALUATION KITS

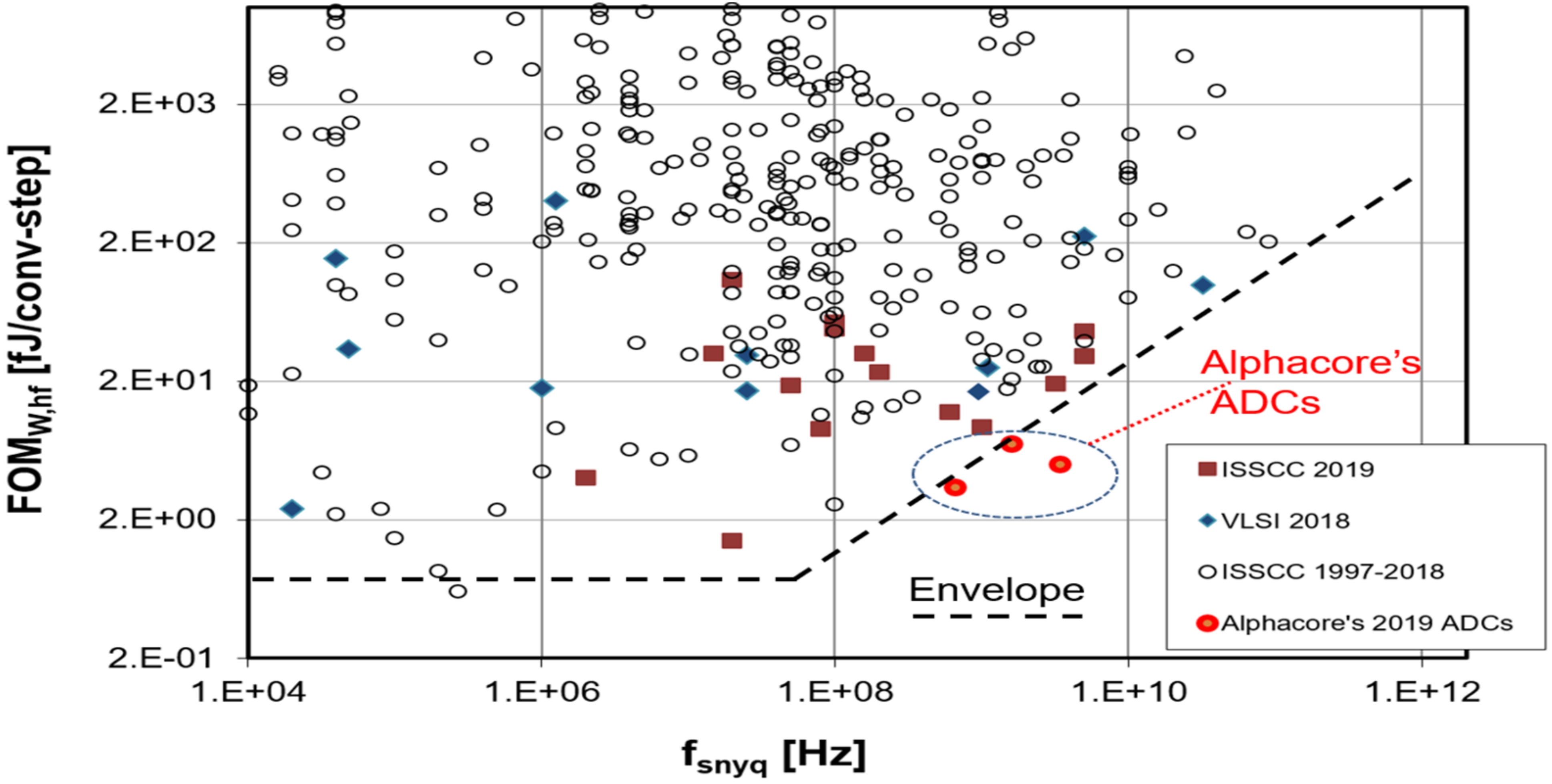
Alphacore Image Sensor evaluation kits are available to allow easy characterization and assessment, enabling users to evaluate the sensor performance in their benchtop prototype or test system, prior to design integration.

Our hardware and software suite enables sensor and camera configuration with features such as triggering, still image capture, high-speed video recording, and image analysis.

Alphacore's high performance data converter IP list

	A10500M	A9B1G	A10B2G	A6B20G		A7B6G, 7bit, 6GS/s Digitally Folding Flash-SAR Hybrid ADC	A6B6G, 6-bit Digitally Folding Flash ADC
Status	Tested	Tested	Tested	Tested with a QFN package as a 4-bit ADC	Expected test results with high-speed package	In fabrication	In fabrication
Sampling Rate (GS/s)	0.56	1	2.4	10	>20	>6.25	>6.25
Resolution (bits)	10	9	10	4	6	7	6
ENOB (bits)	7.9-8.5	7.2-7.7	7.9-8.5	3.3 – 3.7	>4.9	>5.3	>5.3
Input bandwidth (GHz)	>1	>5	>1.5	5	20	20	20
Power(mW)	1.2	2.1	6	<380	<400	16	14
Comments	Offered as an IP block with or without a full-data-rate output interface.	Offered as an IP block with or without a full-data-rate output interface.	Offered as an IP block with or without a full-data-rate output interface.	Offered as an IP block with or without a full-data-rate output interface. Plan is to also offer the ADC as packaged chips.		Main purpose of this ADC core is to be used as a building block of time-interleaved >20GS/s ADCs	Main purpose of this ADC core is to be used as a building block of time-interleaved >20GS/s ADCs

Alphacore's Ultra Low Power ADCs Walden Chart comparison: FOM vs Speed



Other Relevant IP

IP type	Process	Status
10b, 500MSPS, 2GHz, 1.2mW ADC core (radiation tolerant, 100krad)	STMicro 28nm	Evaluated
9b, 1GSPS, 2GHz, 2.7mW ADC core (radiation tolerant, 100krad)	STMicro 28nm	Evaluated
10b, 3GSPS, 3GHz, 18mW ADC core (radiation tolerant, 100krad)	STMicro 28nm	Evaluated
6b, 20GSPS, 20GHz, 220mW ADC core (radiation tolerant, 100krad)	STMicro 28nm	Evaluated
Rad-hard multi-channel, 10-bit, 50MSPS, 7mW ADC ASIC (300krad)	XFAB 180nm	Under evaluation
Rad-hard multi-channel 12bit 100MS/s, 90mW ADC ASIC (300krad)	XFAB 180nm	Under evaluation
Rad-hard multi-channel 50-200 ns rise time, 1GHz CSA ASIC with (300krad)	XFAB 180nm	Under evaluation
Rad-hard, 12-bit, 50MSPS, 9mW ADC (300krad)	ON Semi 180nm	Under evaluation
6b, 5GSPS, 16GHz, 25mW ADC core (radiation tolerant, 100krad)	STMicro 28nm FDSOI	Taped out
10b, 5GSPS, 36mW, 3GHz ADC core (radiation tolerant, 100krad)	STMicro 28nm FDSOI	Tapeout Oct 2019
8b, 100GSPS, 40GHz, 80mW ADC core	STMicro 28nm FDSOI	Under design
12b, 500MSPS DAC (radiation tolerant, 100krad)	UMC 110nm, GF 55nm	Evaluated
6GHz – 13GHz tunable, 360fs jitter PLL (radiation tolerant, 100krad)	TSMC 130nm	Evaluated
12Gb/s transceiver I/Os (radiation tolerant, 100krad)	STMicro 28nm FDSOI	Evaluated

Other Relevant IP

IP type	Process	Status
Rad-hard 56Gb/s PAM4 Transceiver (1Mrad)	TSMC 28nm	Tapeout in 2020
Rad-hard 27b dynamic range 256 X 256 IR DROIC (300krad)	ON Semi 180nm	Tapeout Sep 2019
Rad-hard 20b dynamic range 32 X 32 flash LIDAR receiver (300krad)	ON Semi 180nm	Tapeout ready as of June 2019
Rad-hard 1Mpix, 10,000fps videocamera, 300krad	XFAB 180nm	Under evaluation
Rad-hard DC-DC converter, 14V-to-1.5V, 7A, 1Mrad	ON Semi 0.35um	Prototype tested (product chip under testing)
Rad-hard Li-Ion Battery monitor, 300krad	TSMC 180nm	Tapeout completed in June 2019
In-package chip use time monitor	TSI 180nm	Under evaluation
On-chip identification and authentication monitor	TSMC 180nm	Evaluated (First prototype demoed)
Rad-hard reconfigurable satellite power distribution ASIC, 300krad	XFAB 180nm	Tapeout August 2019
12b, 6GSPS DAC	GF 22nm FDSOI	Tapeout Fall 2019
12b, 1TSPS Waveform Digitizer ASIC	GF 22nm FDSOI	Tapeout Fall 2019
Sensor self-calibration monitor/controller	TSMC 180nm	Taped out July 2019
Rad-hard 56Gb/s PAM4 Transceiver (1Mrad)	TSMC 28nm	Tapeout in 2020
Rad-hard 27b dynamic range 256 X 256 IR DROIC (300krad)	ON Semi 180nm	Tapeout Sep 2019

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Acknowledgement

Work on this program was funded by Department of Energy / Nuclear Physics, Grant #DE-SC0013232.

We especially appreciate the guidance by Drs. Manouchehr Farkhondeh and Michelle Shinn.

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ROBUST HIGH-PERFORMANCE MICROELECTRONICS

Questions? Thank you!

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