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

• 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’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
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

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).

Image before irradiation

...and after 10krad

[Courtesy: Vision System Design]
## Program Goals

<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
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</table>
| 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                 | 1 MeV neutron eq. fluence 1*10^14n/cm^2                                                                                                             |
Camera Irradiation Tests at 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
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 European Space Agency

Data from D. Hiemstra et al, NSREC REDW2018
Radiation Effects on Electronics (2)

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

2. Single event effects (SEEs):
   - 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 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

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...)
  - 0.35µm 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 $t_{ox}$

Radiation tolerance obeys a $t_{ox}^2$ law

0.18µm process

0.35µm 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

Strategy:

- Special attention (layout) must be paid for I/O transistors
- Provision (schematic) must be made for core transistors

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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 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

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
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

- 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
High Sped Camera Radiation Test

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)
- 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

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
- Alphacore’s team also includes electronics experts with >60 years of combined experience in image sensor and camera development.

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

- 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
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

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

<table>
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<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Status</strong></td>
<td>Tested</td>
<td>Tested</td>
<td>Tested</td>
<td>Tested</td>
<td>Expected test results with high-speed package</td>
<td>In fabrication</td>
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<tr>
<td><strong>Sampling Rate (GS/s)</strong></td>
<td>0.56</td>
<td>1</td>
<td>2.4</td>
<td>10</td>
<td>&gt;20</td>
<td>&gt;6.25</td>
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<tr>
<td><strong>Resolution (bits)</strong></td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td><strong>ENOB (bits)</strong></td>
<td>7.9-8.5</td>
<td>7.2-7.7</td>
<td>7.9-8.5</td>
<td>3.3 – 3.7</td>
<td>&gt;4.9</td>
<td>&gt;5.3</td>
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<tr>
<td><strong>Input bandwidth (GHz)</strong></td>
<td>&gt;1</td>
<td>&gt;5</td>
<td>&gt;1.5</td>
<td>5</td>
<td>20</td>
<td>20</td>
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<tr>
<td><strong>Power(mW)</strong></td>
<td>1.2</td>
<td>2.1</td>
<td>6</td>
<td>&lt;380</td>
<td>&lt;400</td>
<td>16</td>
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<tr>
<td><strong>Comments</strong></td>
<td>Offered as an IP block with or without a full-data-rate output interface.</td>
<td>Offered as an IP block with or without a full-data-rate output interface.</td>
<td>Offered as an IP block with or without a full-data-rate output interface.</td>
<td>Offered as an IP block with or without a full-data-rate output interface.</td>
<td>Main purpose of this ADC core is to be used as a building block of time-interleaved &gt;20GS/s ADCs</td>
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</tr>
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</table>
Alphacore’s Ultra Low Power ADCs Walden Chart comparison: FOM vs Speed
## Other Relevant IP

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

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

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We especially appreciate the guidance by Drs. Manouchehr Farkhondeh and Michelle Shinn.
Questions? Thank you!

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