RADIATION HARDNESS ASSURANCE TEST GUIDELINES FOR PHOTODETECTORS AND IMAGE SENSORS

CONTENT OVERVIEW

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Acronyms

CCD	Charge Coupled Device
CIS	CMOS Image Sensor
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial Off The Shelf
CDTI	Capacitive Deep Trench Isolation
DDD	Displacement Damage Dose
DTI	Deep Trench Isolation
ESCC	European Space Components Coordination
GSFC	Goddard Space Flight Center
IR	Infrared
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
MCT	Mercury Cadmium Telluride
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
RHA	Radiation Hardness Assurance
ROIC	Read Out Integrated Circuit
STI	Shallow Trench Isolation

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1. Project Goals and Objectives

Existing Radiation Test Standards

No Radiation Test Standard Dedicated to Photodetectors and Image Sensors

Visible Image Sensor

- Charge Coupled Devices (CCDs)
- CMOS Image Sensor (CIS)
- Commercial Of the Shelf (COTS) CISs

Infrared Detectors

- Detecting Materials (MCT)
- Readout Integrated Circuit (ROIC)
- Cryogenic Temperatures

What degradation and failures are we looking for ?

How do we test those devices ?

Standard	Title	Date
JEDEC JESD57	Test Procedures for the Measurement of SEE in Semiconductor Devices from Heavy-Ion Irradiation	1996
JEDEC JESD234	Test Standard for the Measurement of Proton Radiation SEE in Electronic Devices	2013
MIL-STD-750-1	Environmental Test Methods for Semiconductor Devices TM 1017: Neutron irradiation TM 1019: Steady-state total dose irradiation procedure TM 1080 SEB and SEGR	2014
MIL-STD-883	Microcircuits TM 1017: Neutron irradiation TM: Ionizing radiation test procedure	2014
ESA-ESCC-25100	SEE Test Method and Guidelines	2014
ESA-ESCC-22900	Total Dose Steady-State Irradiation Test Method	2010
ASTM F1192	Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices	2011
ASTM F1892	Standard Guide for Ionizing Radiation Effects Testing of Semiconductor Devices	2012
ASTM F1190	Practice for Neutron Irradiation of Unbiased Electronic Components	2011
MIL-HDBX-814	Ionizing Dose and Neutron Harness Assurance Guidelines for Microcircuits and Semiconductor Devices	1994
Sandia Nat. Lab. SAND 2008-6983P	Radiation Hardness Assurance testing of Microelectronic Devices and Integrated Circuits: Test Guideline for Proton and Heavy Ion SEE	2008
Sandia Nat. Lab. SAND 2008-6851P	Radiation Hardness Assurance testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance	2008
NASA/DTRA	Field Programmable Gate Array (FPGA) Single Event Effect (SEE) Radiation Testing	2012

1. Project Goals and Objectives

Existing Documents and Main Contributions

Outdated Technologies
Simulation Oriented
Focused on CCDs
Test Report
Expand the content
Not Applied to Detectors

Contribution	Title	Date
Sira Electro-Optics for ESA	Radiation Effects in 2-D IR Sensors [3]	1997
ESA	Predicting Displacement Damage Effects in Electronic Components by Method of Simulation: Literature Survey and Pre-Assessment of Methods [4]	2002
NASA	Proton Test Guideline Development-Lessons Learned [1]	2002
NASA	CCD Radiation Effects and Test Issues for Satellite Designers [2]	2003
Sira Electro-Optics for ESA	Radiation Testing of CCD and APS Imaging Devices [5]	2003
SURREY Ref: 0195162	Displacement Damage Guidelines [6]	2014
ONERA for ESA	Displacement Damage Test Guideline Development [7]	2016
ESA-ESCC-22500	Guidelines for Displacement Damage Irradiation Testing [8]	2019

Project Goals and Objectives

Capture and Sustain NASA Expertise and Capability in Photodetector and Image Sensor RHA

What do we value?

- Best practices, Past Research, Lessons-Learned

From Where?

- Across NASA centers: GSFC, JPL, Ames, LaRC, JSC…

Main objectives:

- Support Photodetector RHA activities
- Maximize the utility of the guidelines for all

How?

- Collaborate to shape the content of the guidelines document to meet current and future needs

1. Project Goals and Objectives

RHA Guidelines

1. Pragmatic
2. Scientific
3. Flexible
4. Collaborative

RADIATION HARDNESS ASSURANCE GUIDELINES FOR PHOTODETECTORS AND IMAGES SENSORS

— Version 1.0 —

NEPP
NASA Electronic Parts and Packaging Program

Alexandre Le Roch
Jean-Marie Lauenstein

Supported by:
NASA Electronic Part and Packaging Program (NEPP)

April 18, 2023

~ 250 pages

01 Context and Future Needs of RHA Tests on Photodetectors and Image Sensors

~ 70 pages

- Positions Photodetectors in Microelectronic Trends and Foresees Future Needs in RHA

02 Fundamentals on Radiation Effects on Semiconductor Devices

~ 60 pages

- Focus on DDD and Ongoing Research Activities

03 Test Method for CCDs and CMOS Image Sensors

~ 120 pages

- Test Setup Requirements and Test Method

2. Guidelines Content Overview

01

Context and Future Needs of RHA Tests on Photodetectors and Image Sensors

What's the content ?

- Overview of the context of photodetectors and image sensor development trends
- Evolving needs for RHA testing
  - COTS CMOS Image Sensors
  - SPAD Imagers
  - Hybrid Infrared Detectors

Who is this for ?

- Junior RHA & Detector System Engineers
- Senior RHA Engineers
- Management

Why is this useful ?

- Get the big picture
  - Anticipate trainings
  - Orient the work force
  - Justify funds
- Align visions among main RHA actors
- Bring expertise to decision-making

2. Guidelines Content Overview

Covers a wide range of technologies and applications from custom to commercial detectors

2. Guidelines Content Overview

02 Fundamentals of Radiation Effects on Semiconductor Devices

What's the content ?

- Overview of radiation effects in semiconductor devices (Silicon)
- Focus on displacements
  - Responsible for hot pixels
  - Dynamics of Defect Creation
  - Damage Factor & NIEL Scaling

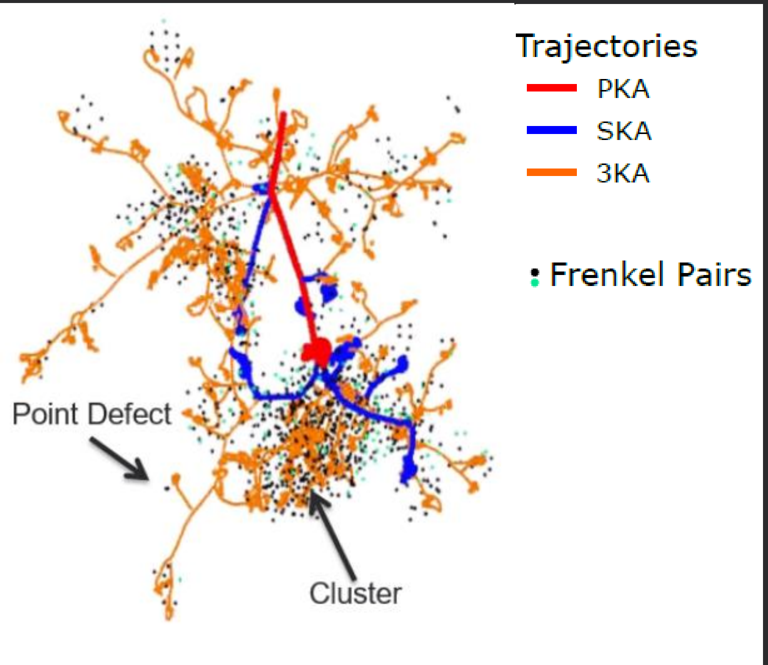
Who is this for ?

- Jr. RHA Engineers → Training
- Sr. RHA Engineers → Updated references
- Instrument/FPA Designers → Understand Limitations

Why is this useful ?

- Get the big picture
  - Physics behind the degradation
  - Understand foundations of test methods and standards
  - Enable new ideas and contributions
- Update on ongoing research activities

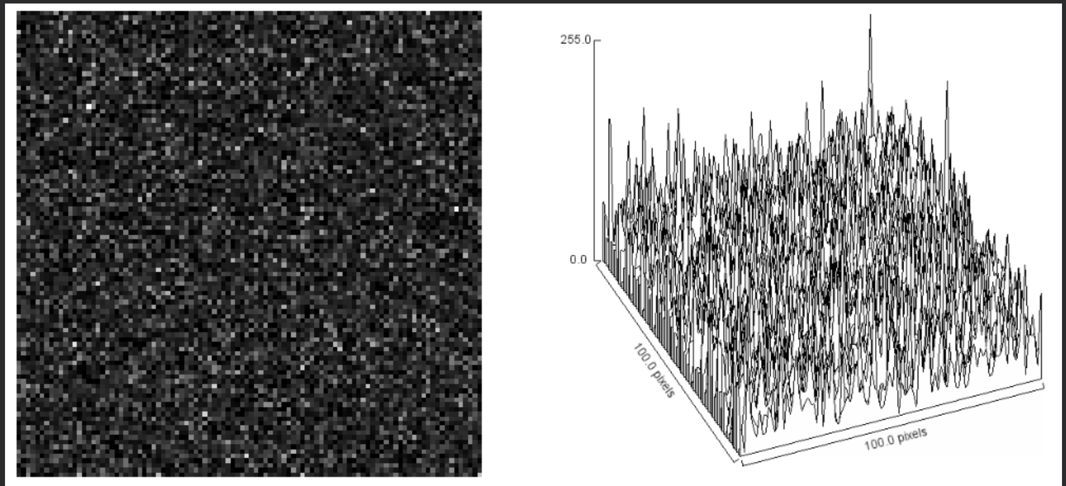
2. Guidelines Content Overview



Courtesy of Antoine Jay, NSREC 2016

Focuses on the physics of displacements and associated damage factor & NIEL scaling concepts

2. Guidelines Content Overview



Focuses on the main performance degradation mechanisms in all photodetectors and image sensors

2. Guidelines Content Overview

03

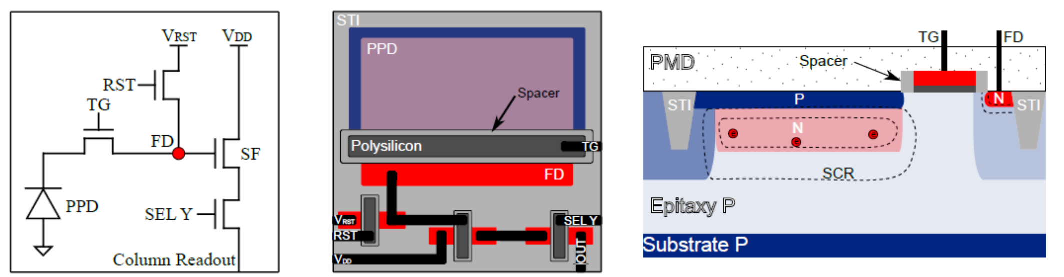
Test Method for CCDs and CMOS Image Sensors

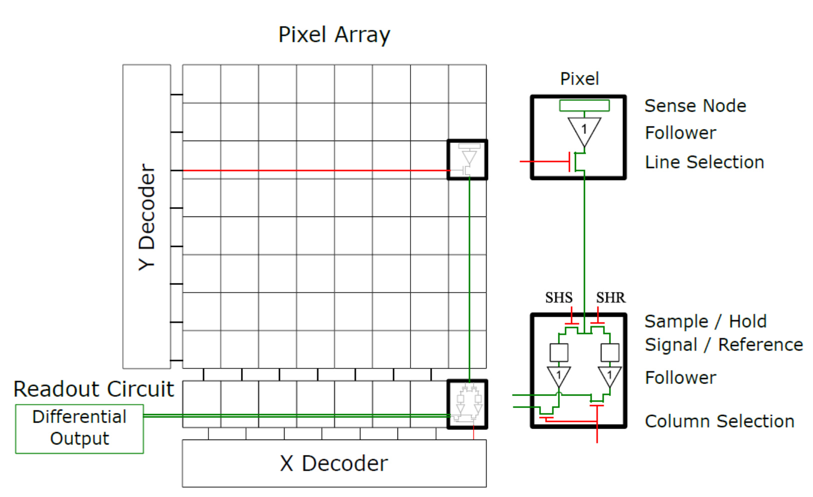
What's the content ?
- Image sensor working principle
- Test method
- Focus on CIS
    - Growing interest
    - Specificities & Vulnerabilities
    - Testing methodology

Who is this for ?
- RHA Engineers → Test Method
- RHA Engineers → Identify Vulnerabilities
- Instrument/FPA Designers → Understand Limitations

Why is this useful ?
- Guide test design & Raise awareness
    - Setup & Equipment & Best Practices
- Understand the origin of the degradation
    - More adaptable to actual needs
    - Enabling new ideas and contributions
- Updated references and ongoing research

2. Guidelines Content Overview





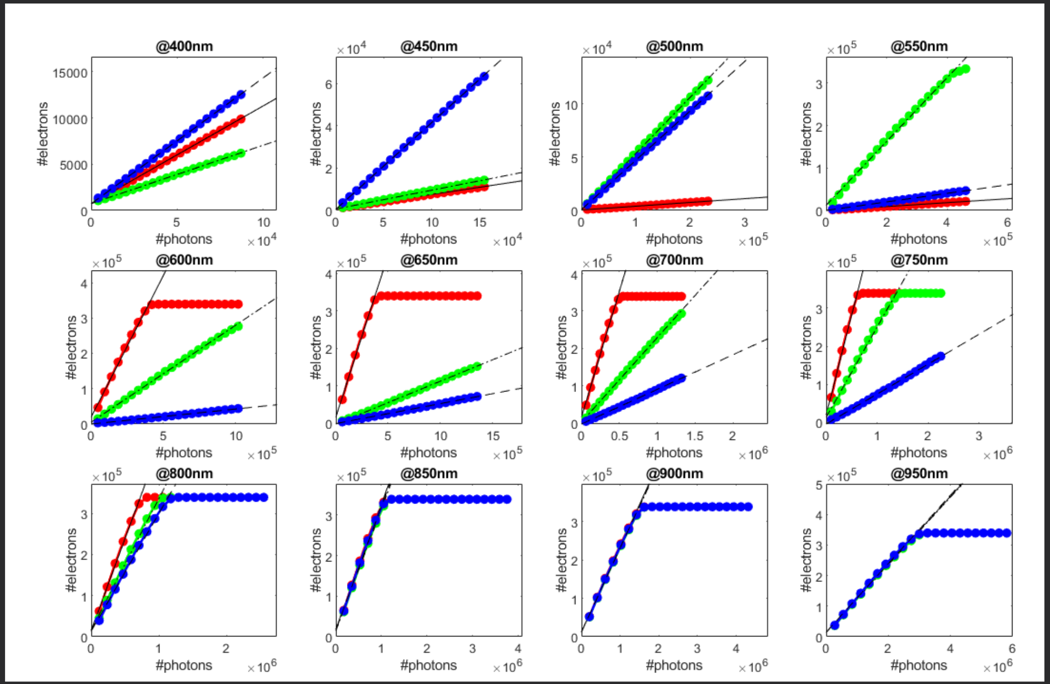
Covers all the basics to understand the device, its vulnerabilities, and the parameters of interest

2. Guidelines Content Overview

Questioning Workflow	Corresponding Sections
What's it for ?	1. Objective
What do I need ?	2. Setup & Equipment
How to do it ?	3. Method
How to deal with data ?	4. Data Processing
Is that normal ?	5. Examples
What does radiation do ?	6. Radiation Impacts
What's that thing ?	7. Common Artifacts

Provides guidance for conducting tests and adaptable solutions to the user's own needs

2. Guidelines Content Overview



Provides real data figures and analysis to present how it looks

3. Scenario Example

Detector RHA Typical Workflow

1

Mission Details
- Life duration & Orbital parameters & Radiation environment

2

Detector
- Irradiative environment at detector level after shielding

3

Ground Test Design
- Energy & Dose & Dose rate

4

Performance Degradation Measurements
- Performance-driving parameters (ex: Dark Current, Dynamic Range, Sensitivity)

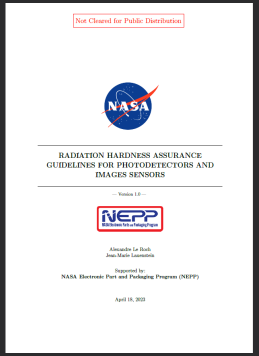
5

Test Report and Actions
- End of life detector performance
- Impacts on mission's goals
- Modifications : Shielding / Operating Temperature / Others…

Radiation Test Standards
Software Tools
Experience

Overlap

RHA Guidelines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3. Scenario example

Who:
Junior RHA engineer

Chap. 2
Chap. 3

Competencies:
Background in electronics

Tasks:
Collaborate with detector s ystem engineer in designing radiation testing of a commercial CMOS Image Sensor

Image Sensor RHA

- Image Sensor
  - Detection
    - Pixel
      - Microelectronic
      - Pixel design
  - Readout Chain
    - Electronics
      - Analog
      - Digital
- Radiation
  - TID
    - Oxide
      - Interface States
      - Build-up Charge
  - DDD
    - Bulk
      - Defects

Operating Image Sensor

Characterizing RadFX

3. Scenario example

Who:

Senior RHA engineer

Competencies:

Expertise in electronics and radiation effects

Tasks:

Collaborate with detector s ystem engineer in designing radiation testing of a commercial CMOS Image Sensor

Chap. 1
Chap. 3

Image Sensor RHA

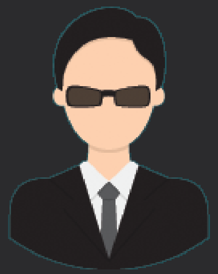
- Image Sensor
  - Detection → Pixel
    - Microelectronic
    - Pixel design
  - Readout Chain → Electronics
    - Analog
    - Digital
- Radiation
  - TID → Oxide
    - Interface States
    - Build-up Charge
  - DDD → Bulk
    - Defects

Operating Image Sensor

Characterizing RadFX

3. Scenario example

Who:
Instrument/FPA Designers



Chap. 1
Chap. 3

Competencies:
Expertise in image sensor characterization and development

Tasks:
Design of a camera based on a commercial CMOS Image Sensor

Image Sensor RHA

- **Image Sensor**
  - Detection → **Pixel**
    - Microelectronic
    - Pixel design
  - Readout Chain → **Electronics**
    - Analog
    - Digital
- **Radiation**
  - TID → **Oxide**
    - Interface States
    - Build-up Charge
  - DDD → **Bulk**
    - Defects

Operating Image Sensor

Characterizing RadFX

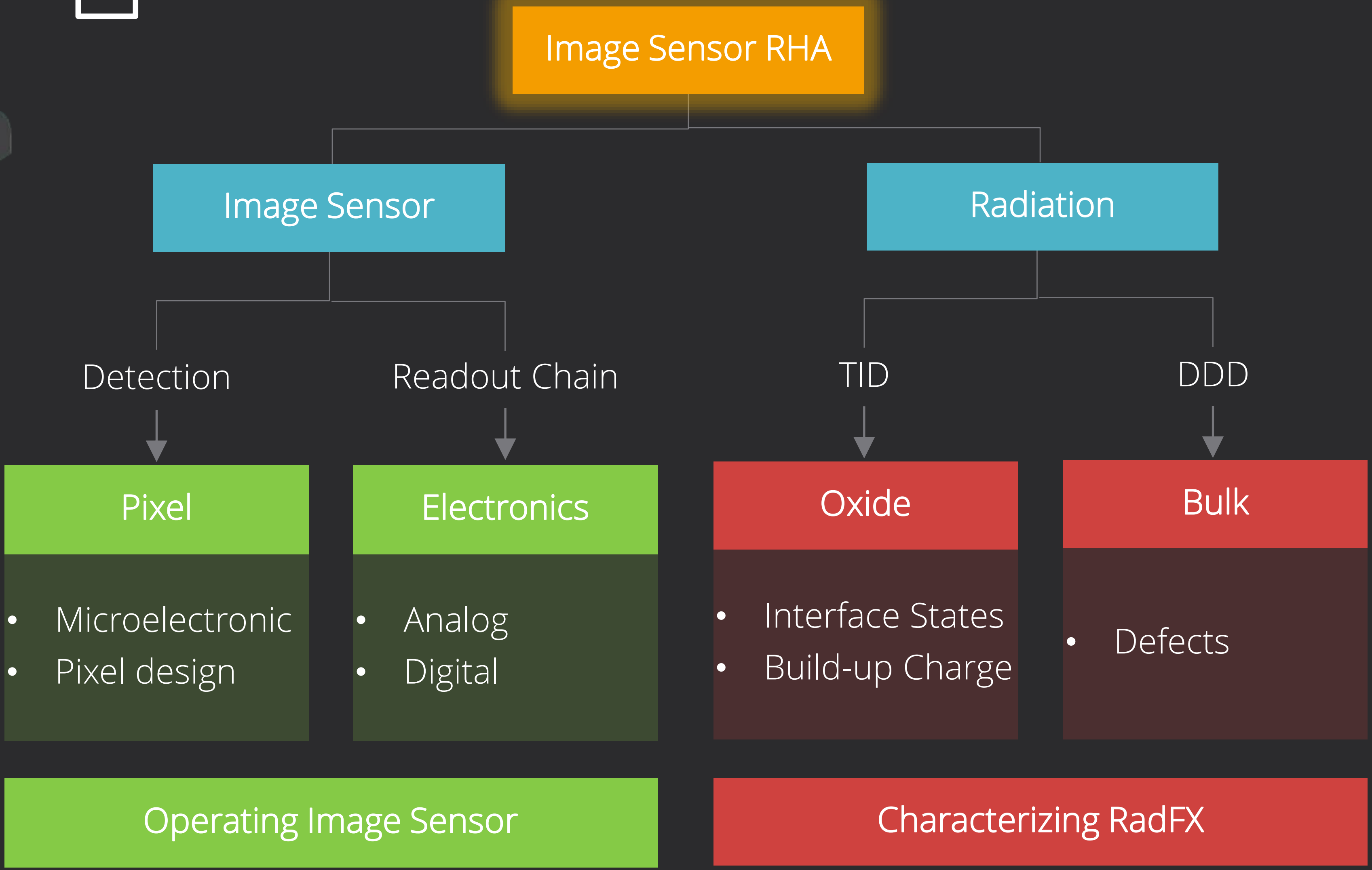
3. Scenario example

Who:
Radiation Team Manager

Competencies:
Knowledge of electronics and radiation effects

Tasks:
Orient radiation engineers, support test platform development, anticipate RHA needs

Chap. 1



4. Next Steps and Conclusion

01 Rising interests and specific needs for Radiation Hardness Assurance (RHA) tests dedicated to photodetectors and image sensors operating in space environments ✓

- Definition & Scope
- Positioning Photodetectors in Microelectronic Trends
- Future Needs in RHA

02 Fundamentals of space radiation environment and radiation-induced degradations on semiconductor devices ✓

- Basic Knowledges & Key Concepts
- Focus on DDD
- Updated References
- Updates on Ongoing Research Activities

03 Charge Coupled Devices (CCD) and Complementary Metal Oxide Semiconductor (CMOS) images sensors ✓

- Identify and Estimate the Radiation Vulnerabilities
- Parameters of Interest
- Test Setup Requirements and Test Method

04 Photodetector Array for UV & Infrared Applications

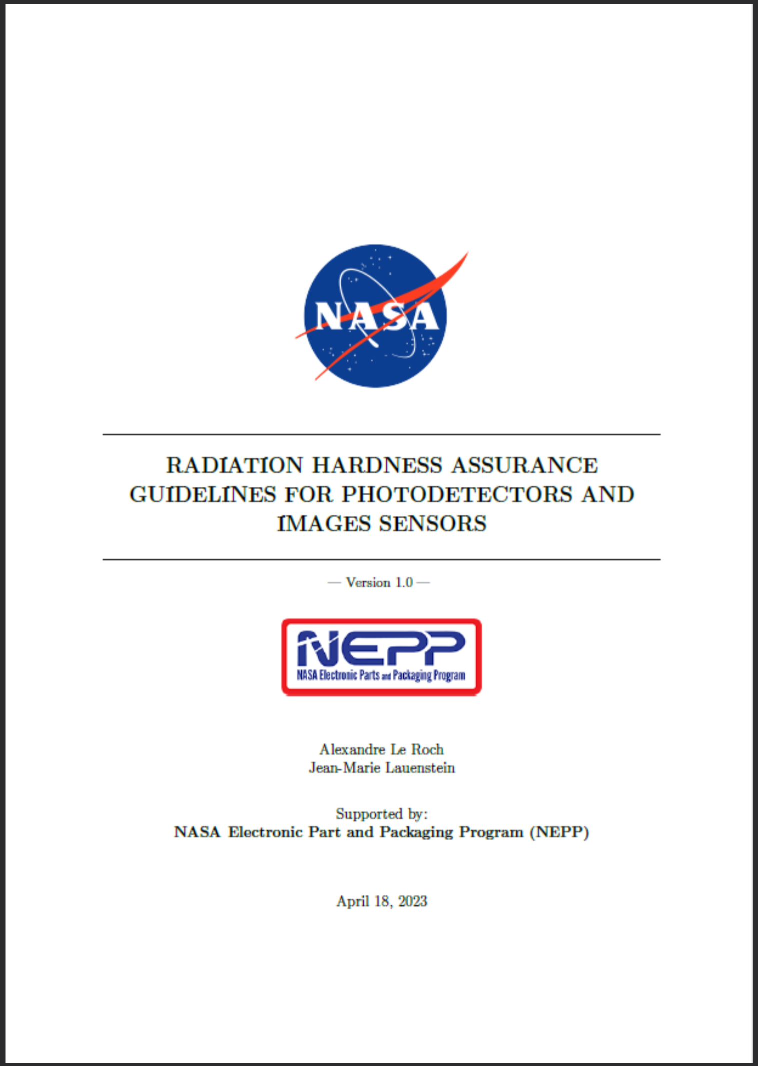
- Identify and Estimate the Radiation Vulnerabilities
- Parameters of Interest
- Cryogenic Test Setup
- Test Setup Requirements and Test Method

4. Next Steps and Conclusion

"Gather useful information in one document."

"Covers central aspects of Image sensor RHA."

"Available on the NEPP website shortly."



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- Test Reports
- Data
- Lessons Learned
- Best Practices

"This is a living document. Feedback will be incorporated."

THANKS FOR YOUR ATTENTION

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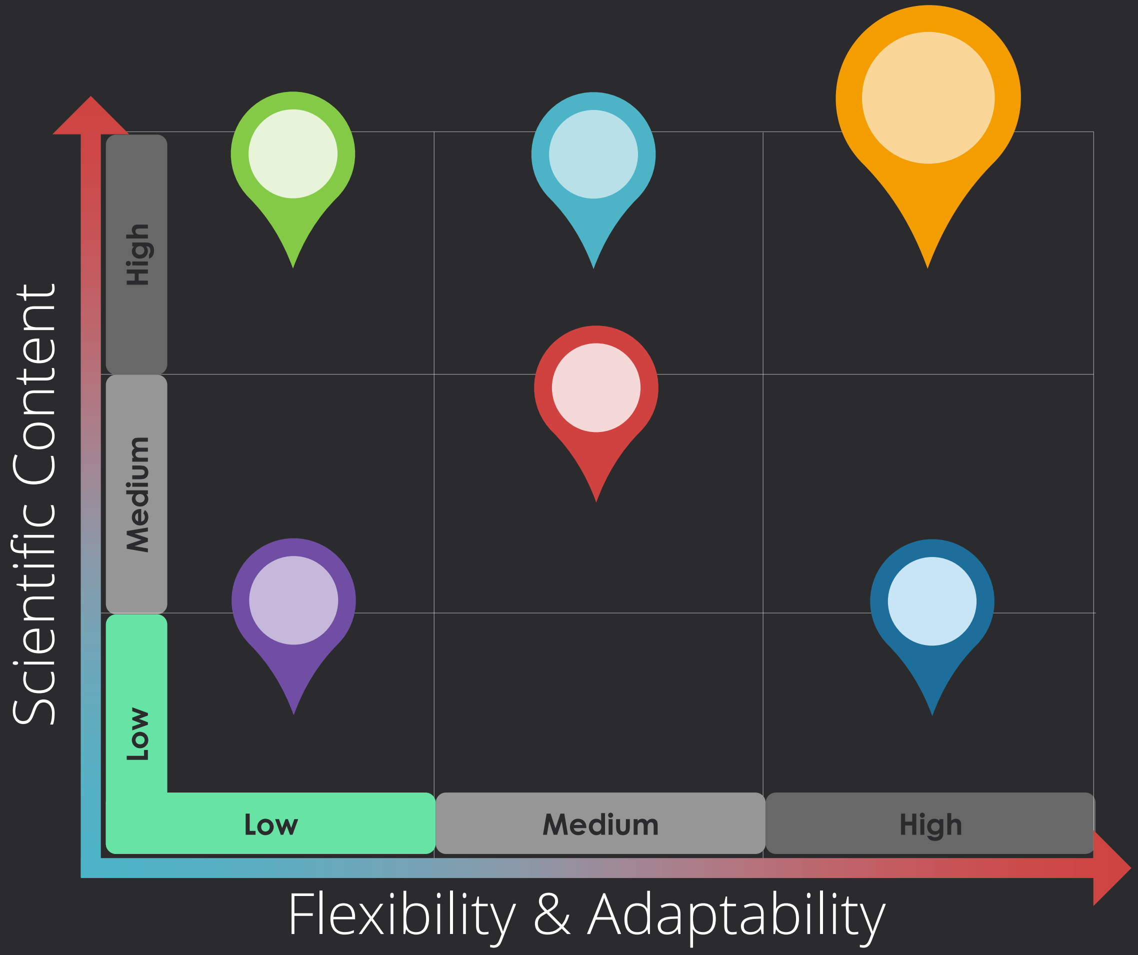
1. Backup slide : Project Goals and Objectives

Radiation Hardness Assurance Guidelines



Documentation

- Literature Review
- Scientific Report
- Test Report
- Mil & ESCC Standards
- Best Practices & Lesson-Learned
- RHA Guidelines

Backup slide : Testing COTS Image Sensors

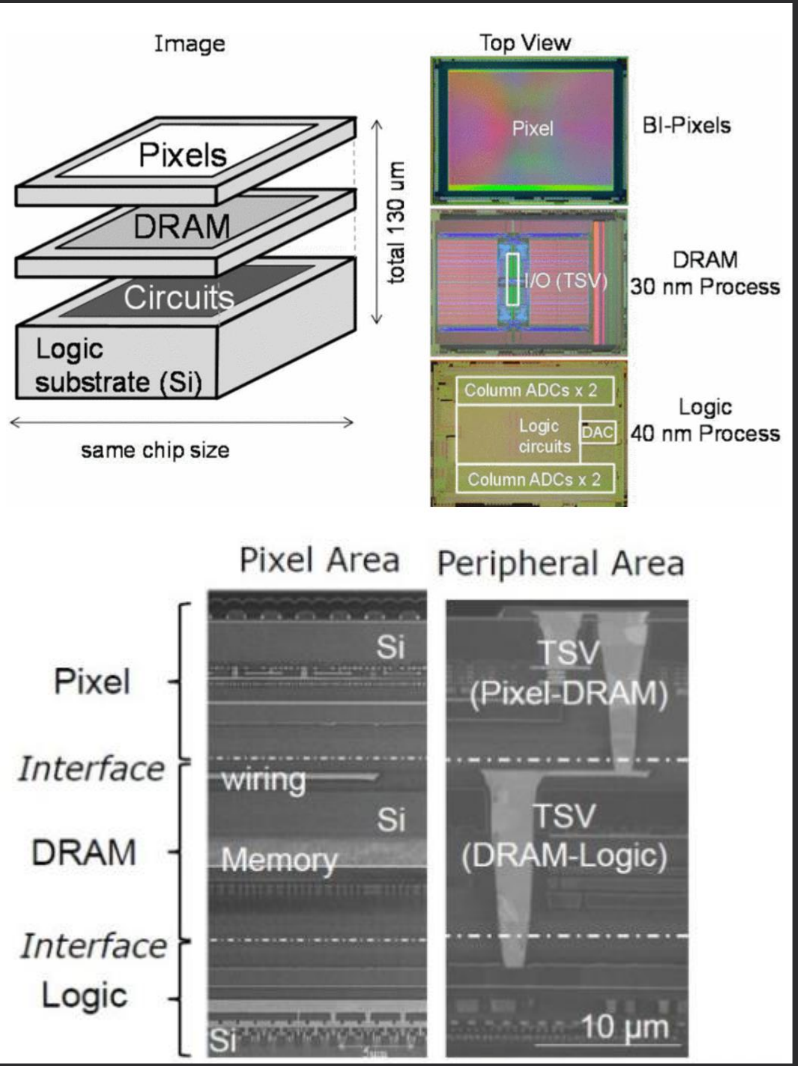
Commercial Of The Shelf (COTS) CMOS Image Sensor

- **Even more complex 3D pixel structures**
  Multilayers, Vertically Pinned Photodiodes, Anti Blooming, Pixel Binning, Dark Current Mitigation…

- **Advanced oxide processes:**
  Shallow Trench Isolation (STI), Deep Trench Isolation (DTI), Capacitive Deep Trench Isolation (CDTI), High-k oxide…

- **Stacking technologies**
  Readout Integrated Circuit (ROIC), Memory DRAM, Logic

- **Increased interest in flying COTS CIS**
  OSIRIS REX instrument, Mars Perseverance’s landing sequence



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Backup slide : What makes photodetectors different ?

Analog detector
- Large in-pixel structures
- Double gate oxide (GO2) MOSFETs
- High voltage swing 2 - 3.3V

Adapted CMOS process for imaging
- GO2 In-pixel MOSFETs
- Photodiode implant
- Doping profile
- Oxides (liner oxides)

Mixed-mode device
- Analog and digital signals

Include optical features
- Antireflecting coating
- Microlens & Color filters