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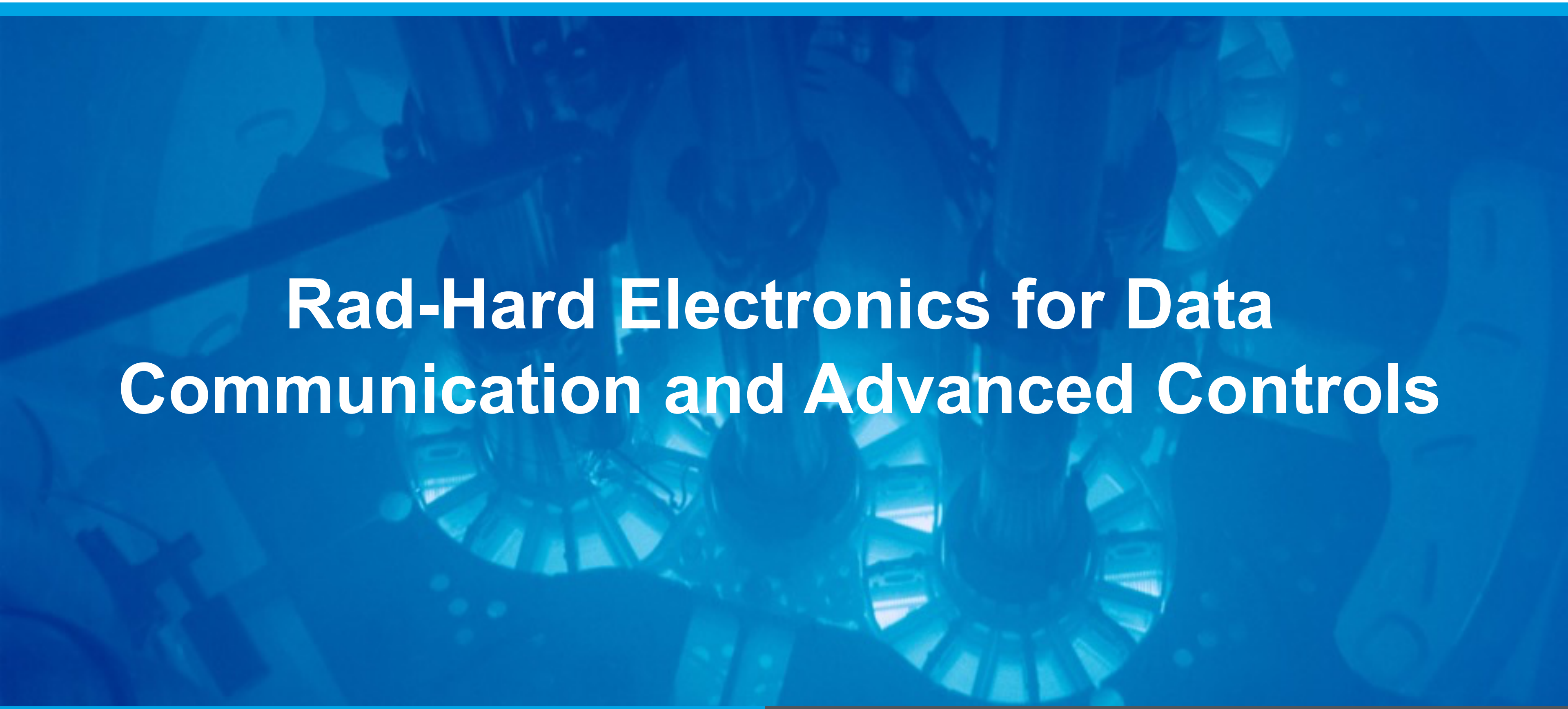


Rad-Hard Electronics for Data Communication and Advanced Controls

Advanced Sensors and Instrumentation
Annual Webinar

November 5, 2020

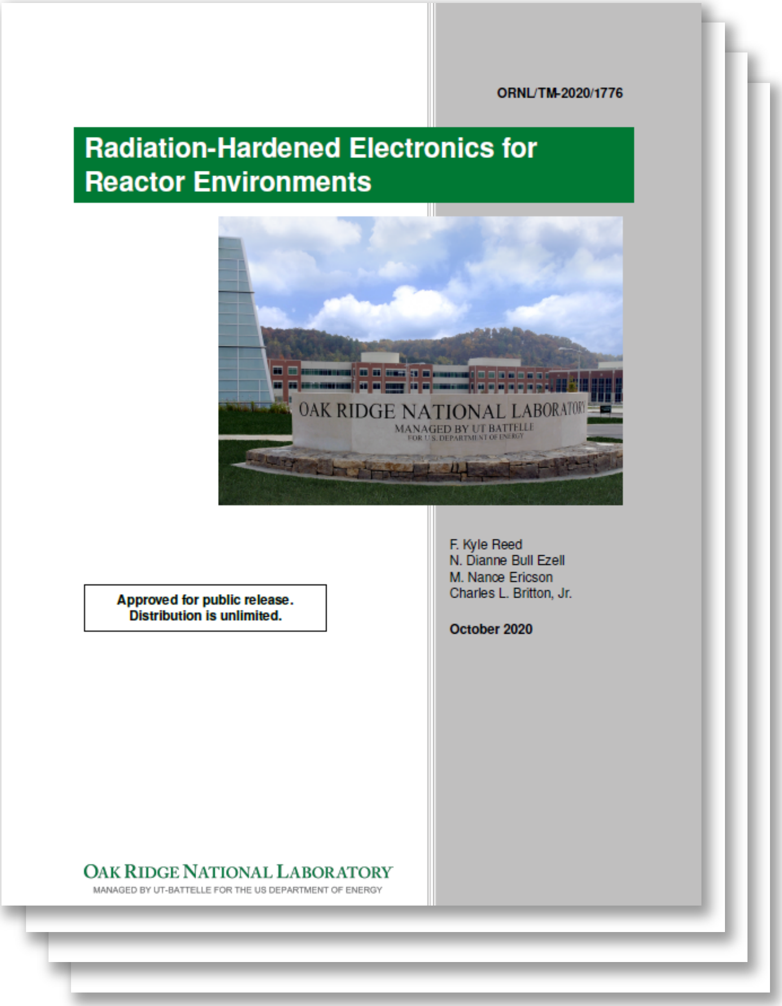
Kyle Reed
Oak Ridge National Laboratory

Project Overview

- Goal and Objective
  - Survey state-of-the-art (SOA) radiation-hardened electronic components and systems for reactor communication, instrumentation, and controls. This survey identifies gaps in technology and suggests future research directions in radiation-hardened electronic systems.
- Participants (2020)
  - Nance Ericson, PI, Oak Ridge National Laboratory
  - Kyle Reed, Oak Ridge National Laboratory
  - Dianne Bull Ezell, WPM, Oak Ridge National Laboratory
  - Chuck Britton, Oak Ridge National Laboratory
- Schedule
  - July 1st – September 30th, 2020

Summary of accomplishments

- Radiation effects of electronics associated with reactor environments are reviewed
- Survey of commercial and research SOA rad-hard electronics is presented
- Gaps in technology space are identified
- Suggestions for establishing future research directions of research are given



ORNL/TM-2020/1776

Radiation-Hardened Electronics for Reactor Environments

Approved for public release.
Distribution is unlimited.

F. Kyle Reed
N. Dianne Bull Ezell
M. Nance Ericson
Charles L. Britton, Jr.

October 2020

OAK RIDGE NATIONAL LABORATORY
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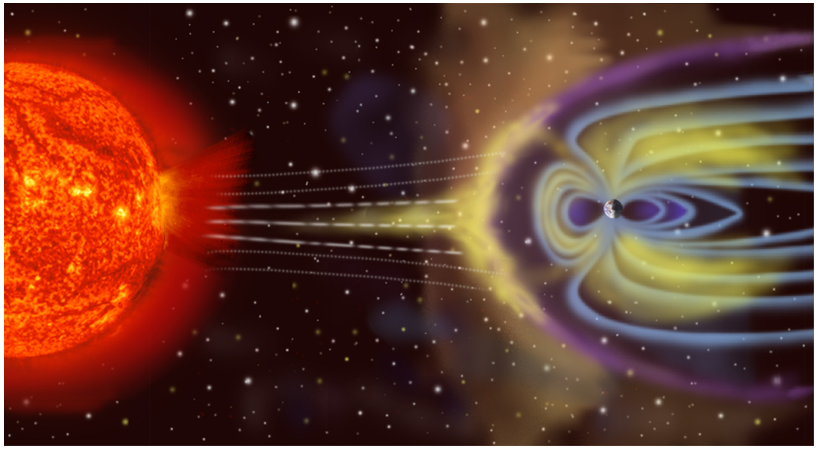
Technology Impact

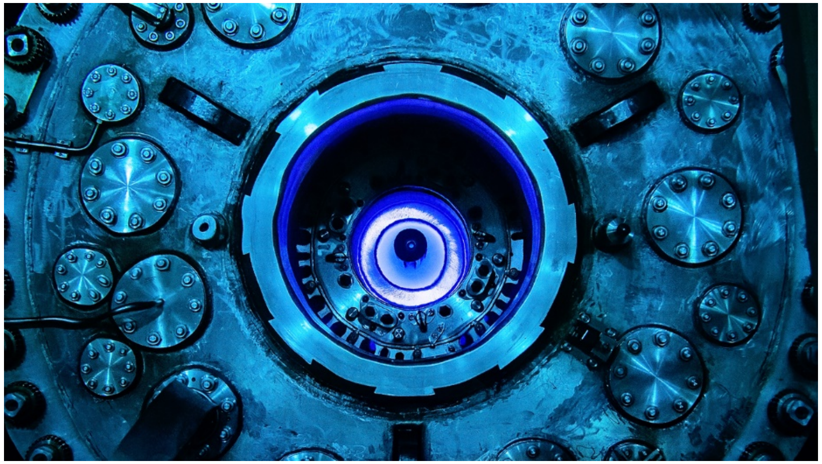
- *Advances the state of the art for nuclear application*
  - The current SOA is identified and can be used to guide research opportunities in both short- and long-term goals.
- *Supports the DOE-NE research mission*
  - A course of research for radiation-hardened electronics that support increasing safety and efficiency is identified.
- *Impacts the nuclear industry*
  - Placing sensors and associated electronics closer to a nuclear reactor core will improve reactor control and operation through increased signal accuracy, precision, and fidelity resulting in safer and more efficient energy production.
- *Will be commercialized*
  - This survey identifies gaps and directions which will benefit researchers and industry to work more cohesively to promote commercialization.

Space Vs. Nuclear Environments

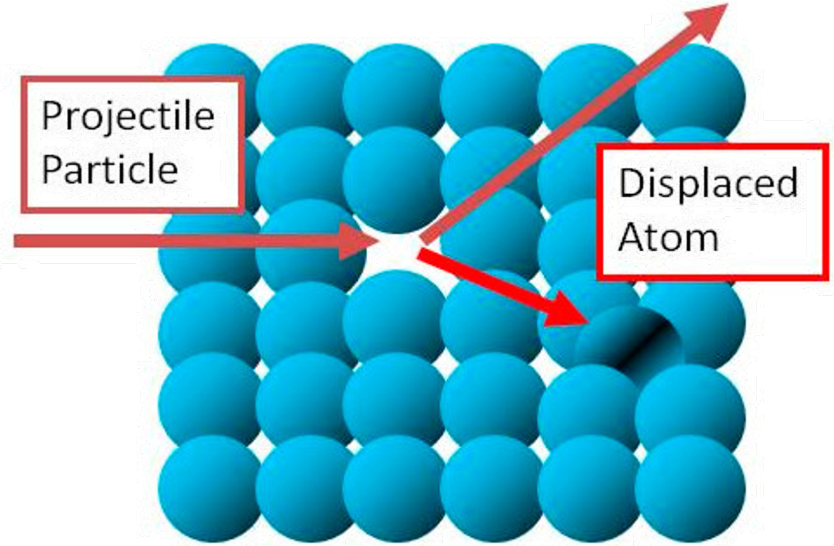
- Space environments
  - Space-rated electronics dominate the radiation-hardened (rad-hard) market
  - The radiation environment in low earth orbit (LEO) and deep space consists of:
    - Galactic cosmic rays and solar winds comprised of **protons** and **electrons**
    - Solar flares and coronal mass ejections generate **protons**, **x-rays**, and **heavy atomic nuclei** with energies ranging from MeV to tens of MeV
    - **Neutrons** if reactor is used for power and/or propulsion
- Terrestrial nuclear environments
  - Nuclear ratings are unclear or omitted from commercial device data sheets
  - **Neutrons** and **ionizing radiation** are associated with terrestrial nuclear environments



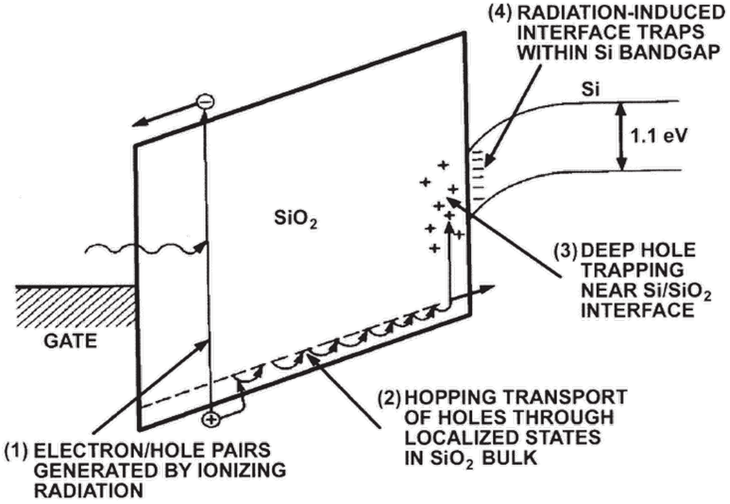
https://www.inverse.com/article/8216-space-radiation-is-quietly-stopping-us-from-sending-humans-to-mars



Radiation Effects on Electronic Components



https://wpo-altertechnology.com/displacement-damage-testing/

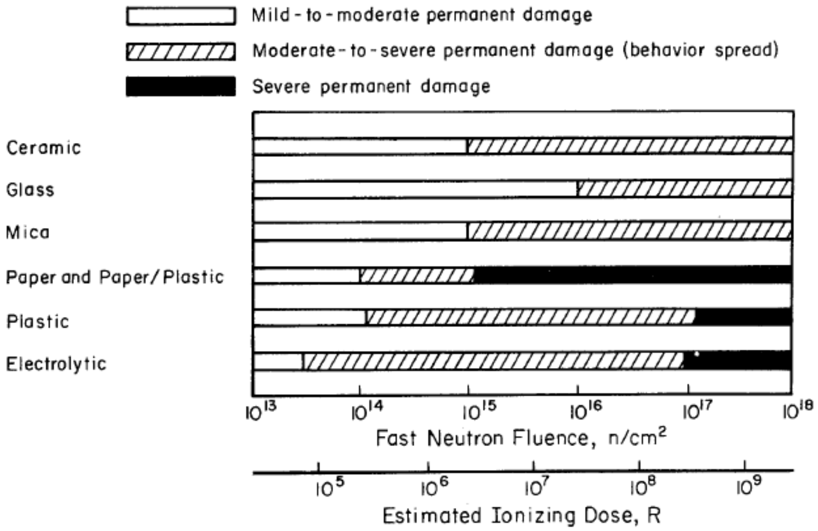


A. Dawiec, Development of an ultra-fast X-ray camera using hybrid pixel detectors, HumanComputer Interaction [cs.HC], Universite de la Mediterranee — Aix-Marseille II, Marseille France (2011)

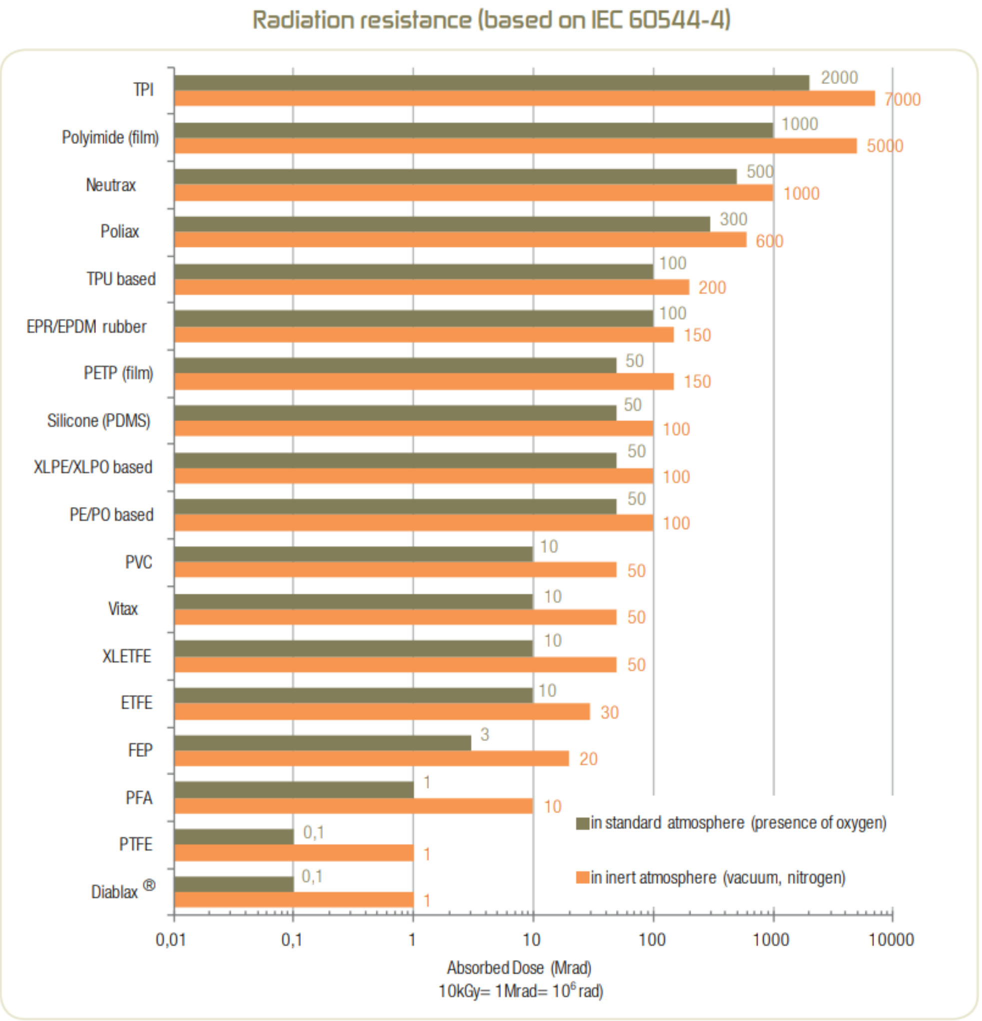
- Neutrons
  - Neutrons will transfer energy to interstitial atoms displacing atoms which may recombine with dopant or impure atoms producing stable defects
  - Minority carrier removal and increased material resistivity are associated with neutron displacement damage
- Ionizing Radiation
  - Compton effect and pair creation from high energy photons create ions in the incident materials
  - Charges are trapped in electrical insulators that generate electric fields and induce currents
  - Dose rates contribute to single event errors such as single event upsets or latch ups

Passive Device and Cabling Limitations

- Dielectric constants and resistivities vary due to neutron displacements
- Induced trapped charges generate electric fields creating biases and noise
- Organic materials release gas that change geometries and degrade structure



C. Hanks and D. Hamman, "Radiation Effects Design Handbook. Section 3: Insulating Materials and Capacitors," NASA, Washington DC, 1971.



https://www.axon-cable.com/publications/AXORAD_CABLESANG.pdf

Device Neutron Hardness Maximums and Device Associated Effects

Technology	Max Fluence (n/cm^2)	Displacement Effects
Diodes	10^{13} - 10^{15}	Increased reverse leakage currents; increased forward voltage threshold
LEDs	10^{12} - 10^{14}	Reduced light intensity
BJTs	10^{13}	Current gain degradation (PNP devices are more sensitive than NPN devices)
JFETs	10^{14}	Increased channel resistivity; decreased carrier mobilities
SiC JFET	10^{16}	Increased channel resistivity; decreased carrier mobilities
MOSFET	10^{15}	Increased channel resistivity; decreased carrier mobilities
CMOS	10^{15}	Increased channel resistivity; decreased carrier mobilities

Note: Radiation specifications represent the maximum recorded of device in category. Specific device variations and ratings must be reviewed alongside the applications for successful design implementation.

Device Ionizing Radiation Hardness Maximums and Device Associated Effects

Technology	Max TID (Gy)	TID Effects
Photodiodes	10^4 - 10^6	Increased photocurrents
LEDs	10^5 - 10^6	0.25 dB luminosity attenuation
BJTs	10^3 - 10^5	Current gain degradation and increased leakage currents
JFETs	$>10^6$	Minimal observable effects
SiC JFET	$>10^6$	Minimal observable effects
MOSFET	10^4	Increasing threshold voltage and leakage currents
CMOS	10^6	Variations in threshold voltage and leakage currents

Note: Radiation specifications represent the maximum recorded of device in category. Specific device variations and ratings must be reviewed alongside the applications for successful design implementation.

Commercial State-of-the-Art Devices

Part Class	Radiation Specifications	Temp (°C)	Manufactures
ADCs	3 kGy TID (Si) SEL 125 (MeV-cm^2/mg)	-55 to 125	TI, STMicroelectronics
DACs	1 kGy TID (Si) SEL 125 (MeV-cm^2/mg)	-55 to 125	TI, STMicroelectronics
Logic	3 kGy TID (Si)	-55 to 125	TI, STMicroelectronics
Opamps & Comparators	3 kGy TID (Si)	-55 to 125	TI, Renesas-Intersil, STMicroelectronics
Power Management	3 kGy TID (Si)	-55 to 125	TI, BAE Systems, Renesas-Intersil, STMicroelectronics
Microcontrollers	2 kGy TID (Si)	-55 to 125	TI, BAE Systems
FPGA	10 kGy TID (Si) SEL >125 (MeV-cm^2/mg)	-55 to 125	Xilinx
Memory	5 kGy TID (Si) 10^{13} particles/cm^2	-55 to 125	TI, BAE Systems

Note: Radiation specifications are max of device in category. Please consult manufacturer documentation for more comprehensive device specification and details.
Note: Neutron fluences are generally omitted as LEO applications dominate the market.

Selected Research and Commercial Systems

- CERN has developed a gigabit transceiver family of custom ICs for high energy physics applications consisting of data acquisition and control (GBT-SCA, 1 MGy TID), serializer/deserializer (GBTx, 1 MGy TID), and bidirectional optical driver and receiver (VTTx, 500 kGy)

- Westinghouse has developed sensors and oscillators for in-core sensing and communications based on vacuum-based electronics

- Rad-hard software defined radio platforms are being pursued by NASA with BAE Systems recently commercializing a 10 kGy TID radio for space applications based on their RAD5545^{TM}

- Cathode ray tube cameras are inherently rad-hard and charge-coupled devices based on CMOS technology have been shown to survive 1 MGy TID with current research seeking 10 MGy cameras

Gaps and Suggested Future Directions of Rad-Hard Electronics

Gaps

- Ratings and classifications do not exist for various reactor environments
- Commercial offerings are qualified for LEO or space flight applications and do not meet the greater TID or neutron fluence requirements of reactors
- Commercially available high complexity circuits for data acquisition and RF systems lag are not readily available for reactor environments
- As reactor generations progress and temperatures increase for better thermal efficiencies, circuit components that can survive beyond 150°C are needed

Future Directions

- Reactor environment surveys
- Standardization of electronic component and system qualifications for reactor environments
- Creation and maintenance of a database compiling present commercial (including space rated devices) and research offerings
- Transitioning research devices to commercially availability

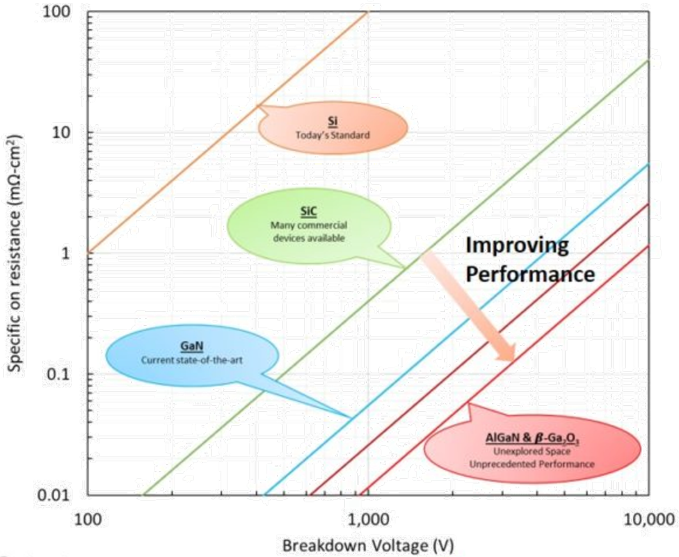
Organizational

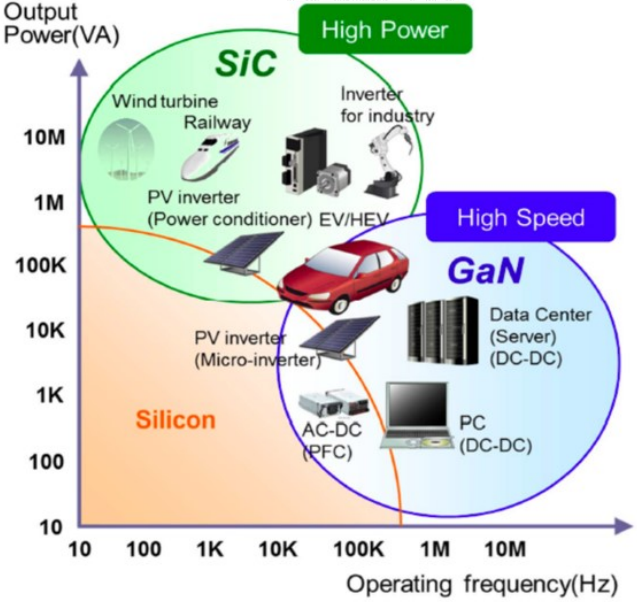
- Increasing device and system complexity
- RF communications, data telemetry, and security
- Non-conventional devices

Technological

Advancing the SOA Technologies

- Sub-micron device processes for more capable circuitry
  - *Benefits:* Decreases charge trapping
  - *Disadvantages:* increases SEE vulnerability
- WBG materials (commonly used for power electronics and high frequency circuitry)
  - *Benefits:* Higher thermal limits, greater doping limits to mitigate neutron damage, some cases better switching efficiency
  - *Disadvantages:* Far less mature for integrated circuits than Si CMOS
- Vacuum electronics
  - *Benefits:* Very high thermal and radiation limits, fast switching frequencies
  - *Disadvantages:* Charge trapping will become more apparent with smaller devices, less mature, greater voltage requirements, degradation of emitters limit longevity





http://grahamlab.gatech.edu/research-2/ultra-wide-band-gap-semiconductor-materials/

Conclusion

- Rad-hard electronics are dominated by the space market
- Nuclear reactor requirements are different than LEO and spaceflight, but commonalities exist
- Directions to >1 MGy TID and 10^{16} n/cm^2 fluences are understood
- Technological and organizational efforts are required to advance the SOA in research and commercialization of rad-hard electronics for reactors

Questions?

Additional questions can be directed to reedfk@ornl.gov