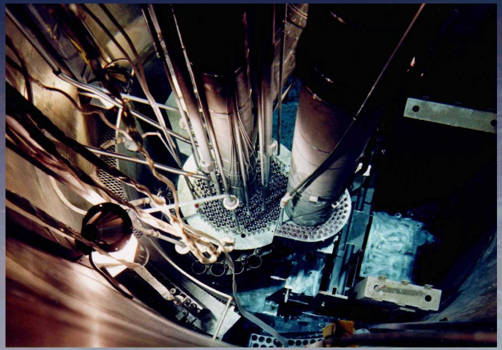

SAND2018-1929C

Potential Impact of WBG and UWBG Devices on Realizing Radiation-Hard Power Electronics

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Albuquerque, NM

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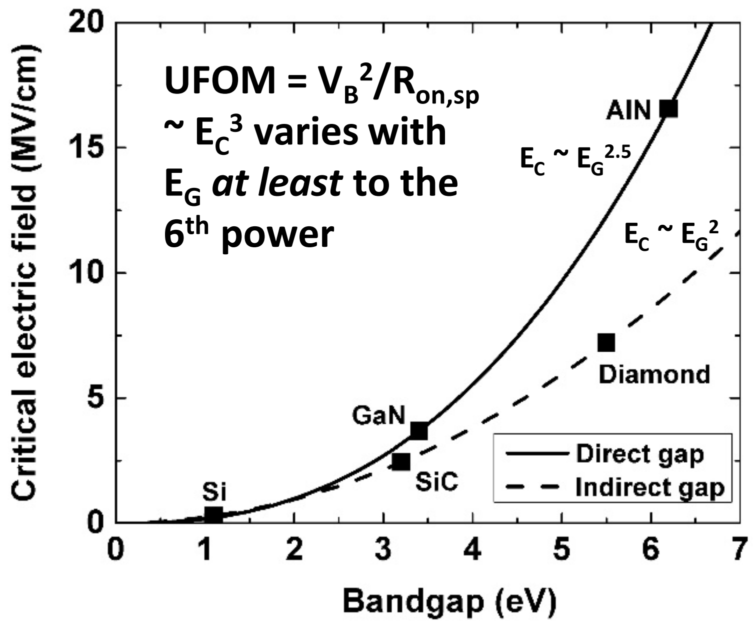
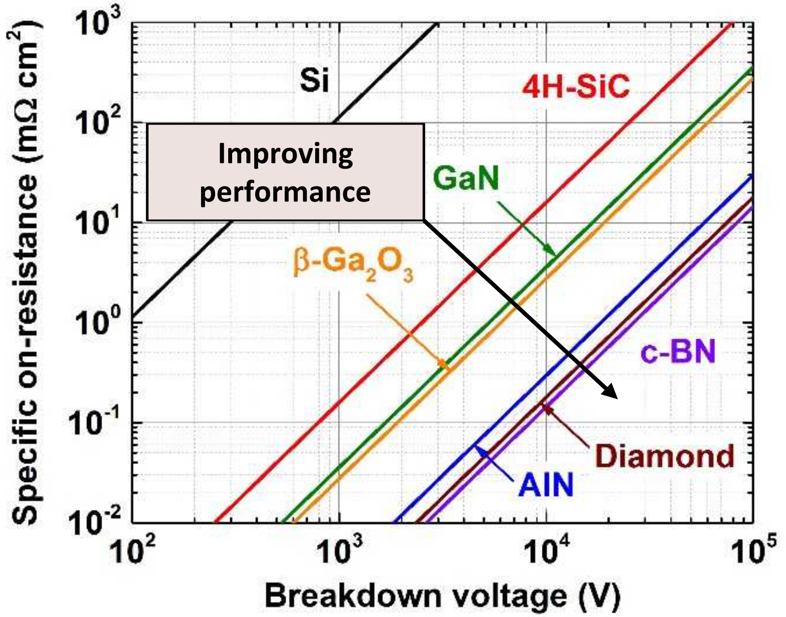
Properties of Wide- and Ultra-Wide-Bandgap Semiconductors

Fundamental Materials Capabilities	Conventional		WBG		UWBG
Property	**Si**	**GaAs**	**4H-SiC**	**GaN**	**AlN**
Bandgap (eV)	1.1	1.4	3.3	3.4	6.0
Critical Electric Field (MV/cm)	0.3	0.4	2.0	4.9	13.0

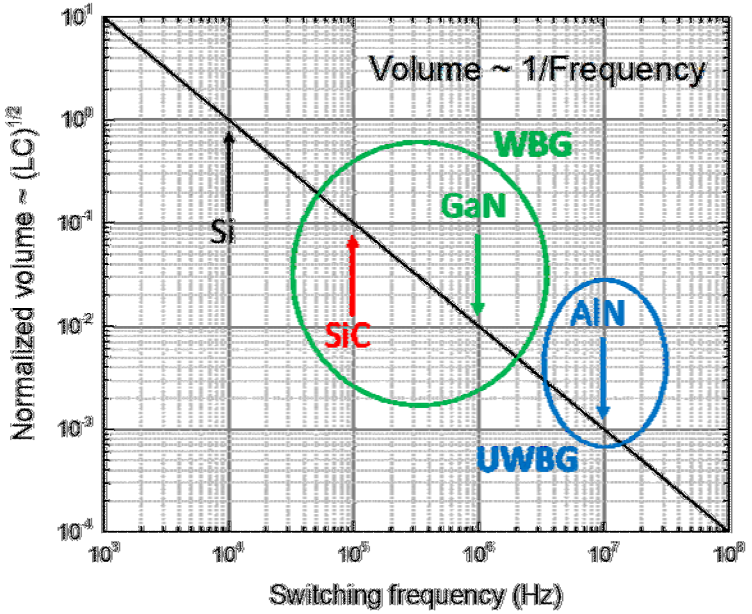


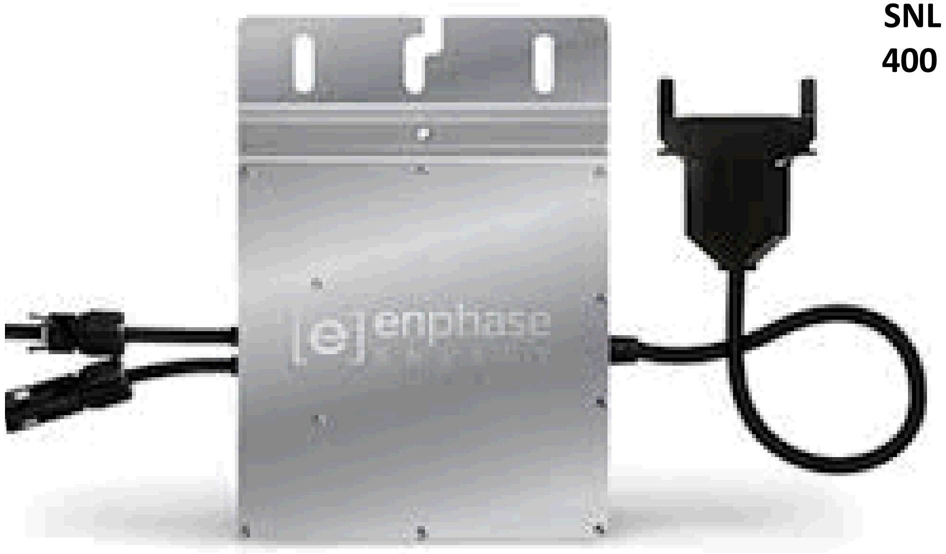


Unipolar FOM = $V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$

Hudgins et al., *IEEE Trans. Pwr. Elec.* 18, 907 (2003); J. Y. Tsao et al., *Adv. Elec. Mat.* 4, 1600501 *(2018)*

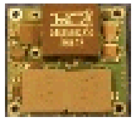
Semiconductor Material Properties Dictate System Volume and Weight





SOA commercial microinverter
250 W in 59 in^3 → 4.2 W/in^3

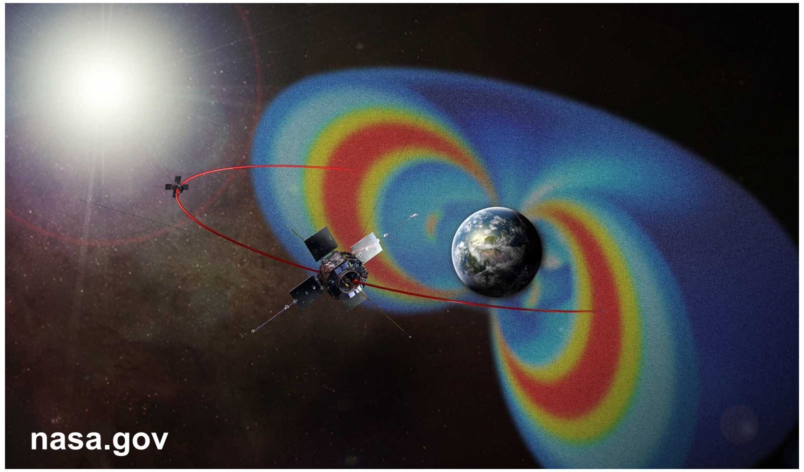
SNL GaN HEMT microinverter
400 W in 2.4 in^3 → 167 W/in^3

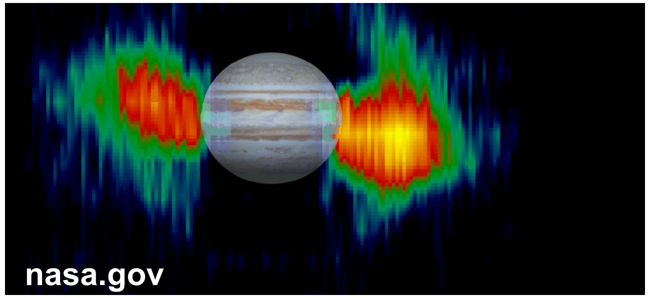


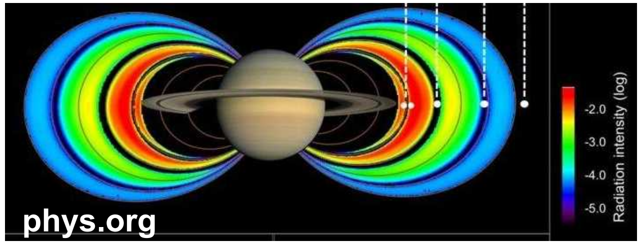
Over an order of magnitude improvement in power density is enabled by WBG semiconductors compared to Si, and further improvements may be possible with UWBG semiconductors

Rad-Hard Power Electronics May Enable Extended Space Missions

- Energetic charged particles from solar wind and cosmic rays are present in the solar system
- High concentrations of charged particles exist around Earth …
  - Inner Van Allen belt – 1,000 km - 6,000 km above Earth
    - 100s keV electrons
    - Up to 100 MeV protons
  - Outer Van Allen belt – 13,000 km – 60,000 km above Earth
    - 100 keV – 10 MeV electrons
    - Protons and other ions, ie alpha particles and other elements
    - For protons of energy 1.0 MeV and higher, flux is as high as $2x10^7$ p/sec/cm^2 (magnetic equator at ~3 Earth radii, normal conditions)
- Radiation belts exist around outer plants as well, i.e. Jupiter, Saturn
- Radiation exposure of space craft components influences design, flight plans, and mission time





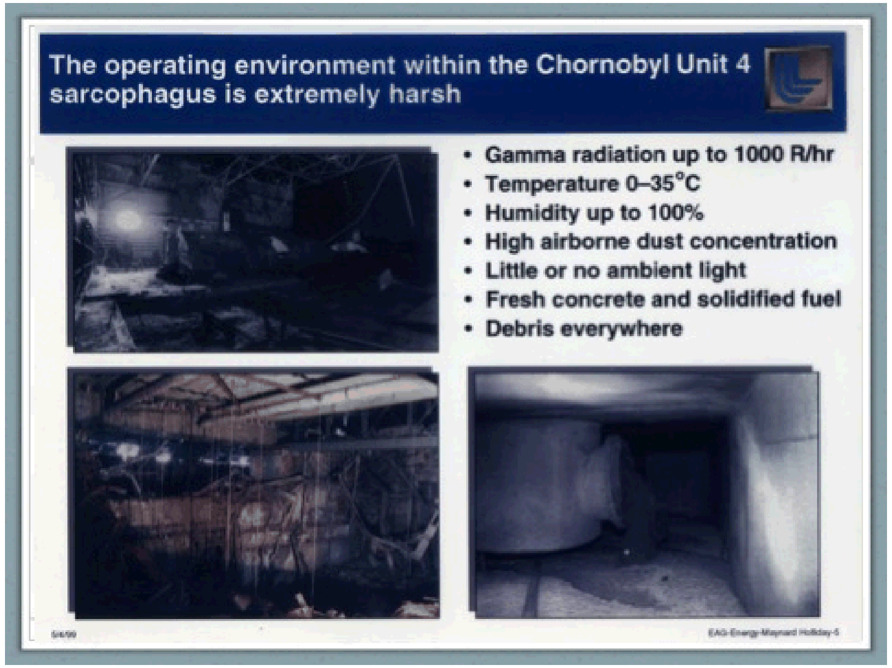


Rad-Hard Power Electronics May Enable Improved Disaster Response

- Nuclear reactor incidents are low probability, but high consequence when they do occur. The Fukushima Dai-ichi reactor incident demonstrated how unprepared response crews are to handle such a crisis with environments too hazardous for humans to enter.
- Robotics technology is critical in response to these types of incidents, but is often used in an ad-hoc scenario with what ever is available.
- Rad-hard power electronics may be an important component for extending the operation of robots in harsh radioactive (as high as 1000 Rad/hour gamma) environments.


Dai-ichi Reactor Buildings – Post Incident


Work at Dai-ichi – Post Incident



Radiation Damage Depends on Several Factors

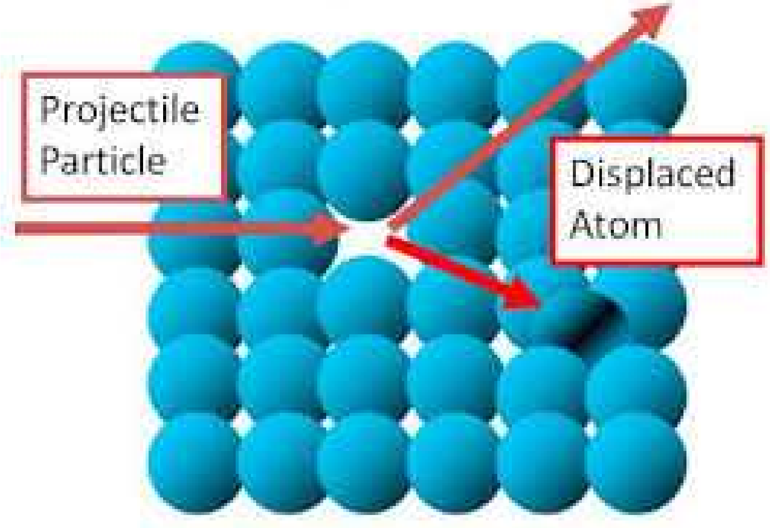
- *Radiation Damage* depends on
  - Dose
  - Dose rate
  - Damage mode
- *Radiation Damage modes* depend on
  - Type of Particle
  - Particle energy
  - Initial condition or bias of the material
- Particle density flux is given ϕ in particles/sec·cm^2
- Particle fluence is the flux integrated over total exposure time given Φ in particles/cm^2
- The Dose is the energy deposited per gram of material

$$1 \text{ rad} = 0.01 \text{ J/kg} = 6.24 \cdot 10^{13} \text{ eV/gram}$$

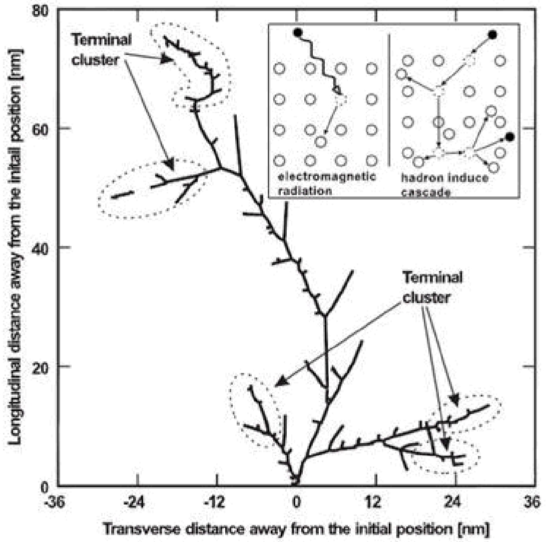
- Dose rate is given in units of rads/sec

Displacement Damage Involves a Change to the Lattice

- *Displacement Damage* is caused by a nuclear collision that knocks an atom from its lattice site
- Changes the orientation of atoms in a lattice
- Displacement Damage typically caused by particles with mass
  - Neutrons
  - Protons
  - Alpha particle
  - Heavy Ions
- Can be caused by very high energy photons
- Displacement damage affects carrier mobility, material resistivity, generation and recombination lifetimes
- Displacement damage is a mechanism of Non-Ionizing Energy Loss (NIEL)

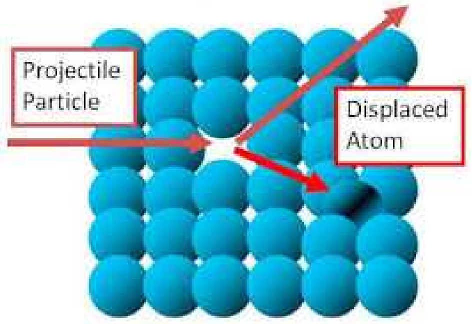


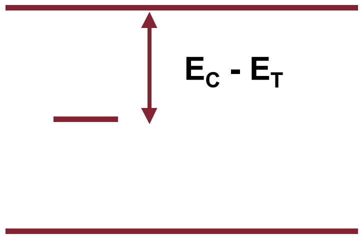
Displacement damage will cascade in a complex pattern

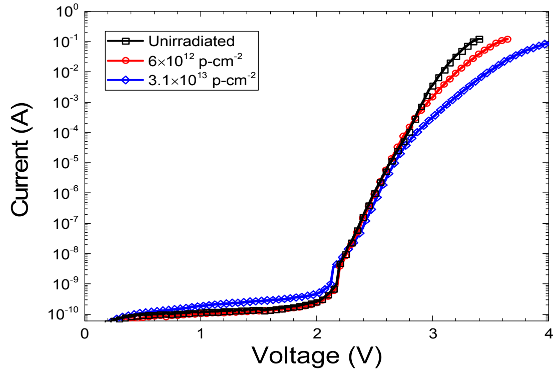


C. Claeys, E. Simoen; "Radiation Effects in Advanced Semiconductor Materials and Devices; Springer-Verlag; 2002

Displacement Damage Effects May Change Device Properties



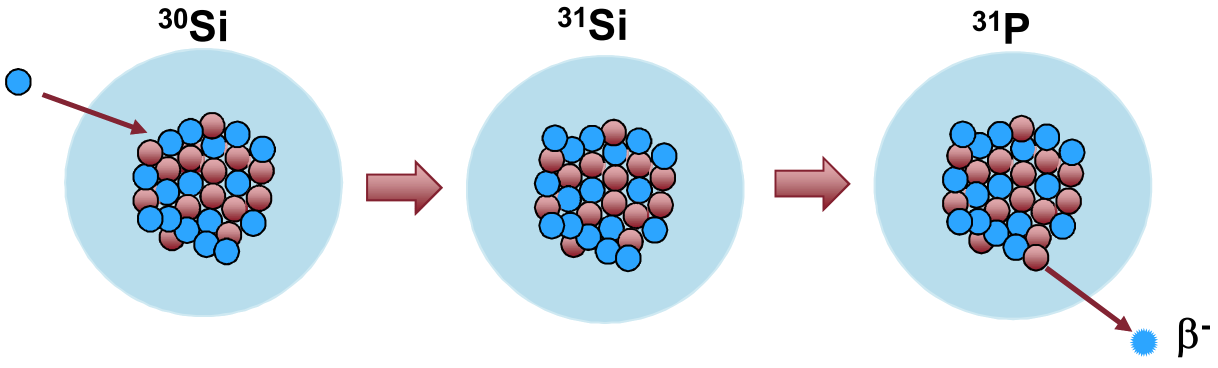


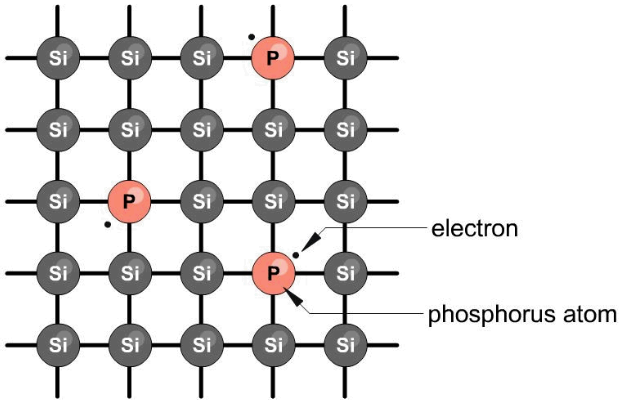


- Deep levels (“Traps”) are introduced into the semiconductor bandgap by displaced atoms
  - Due to broken crystal symmetry
- These deep levels can cause a number of changes to device performance
  - Change in doping, hence change in breakdown voltage (may affect drift region and edge termination)
  - Carrier recombination and generation via deep levels affects forward and reverse bias currents (e.g. reverse saturation current in a pn diode)
  - Change in carrier lifetime may impact switching speed (e.g. reverse-reco0very in pn diode)
- *Radiation-induced changes at the atomic scale may have significant system-level impact!*

Transmutation Changes the Chemical Composition

- Inelastic neutron absorption can lead to *Neutron Transmutation Doping (NTD)*
- Transmutation of *Si* into *P* results in n-type doping





- Other material transmutations

$$^{70}\mathrm{Ge} + n \longrightarrow {}^{71}\mathrm{Ge} \longrightarrow {}^{71}\mathrm{Ga} + \upsilon_e$$

$$^{74}\mathrm{Ge} + n \longrightarrow {}^{75}\mathrm{Ge} \longrightarrow {}^{75}\mathrm{As} + \upsilon_e^-$$

31	32	33
Ga	Ge	As
69.723	72.63	74.921

Ionization Creates Charge Carriers

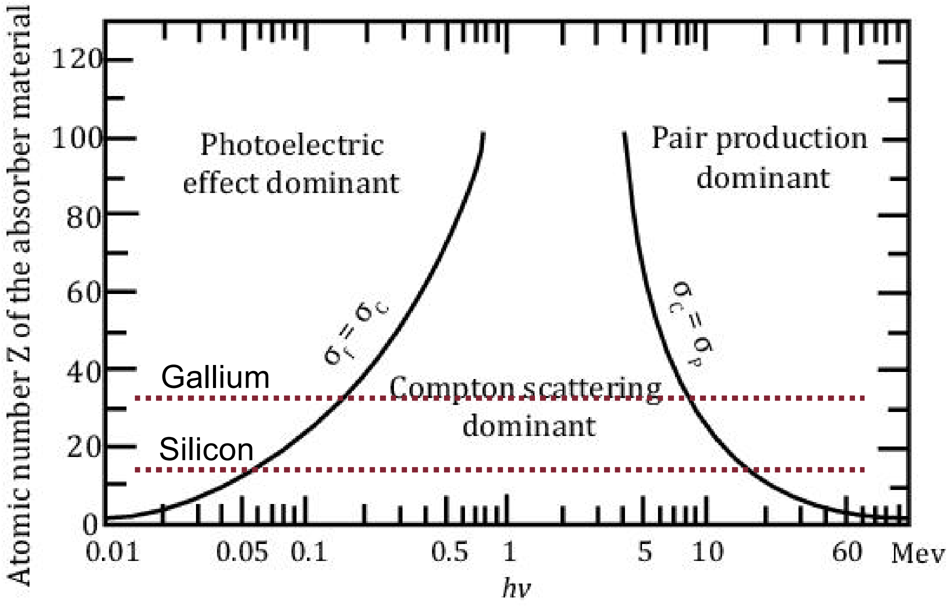
- The photon is a "packet" of electromagnetic energy; Photon energy is proportional to frequency, inversely proportional to wavelength, usually given in electron volts (eV)

$$E_{ph} = \frac{hc}{\lambda} = h\nu$$

- Total energy or power is related to the product of photon energy and the number of photons
- Different interactions take place
  - Photoelectric effect
  - Compton Scattering

$$\frac{E_{ph}}{E_{eh}} \text{ carriers generated}$$

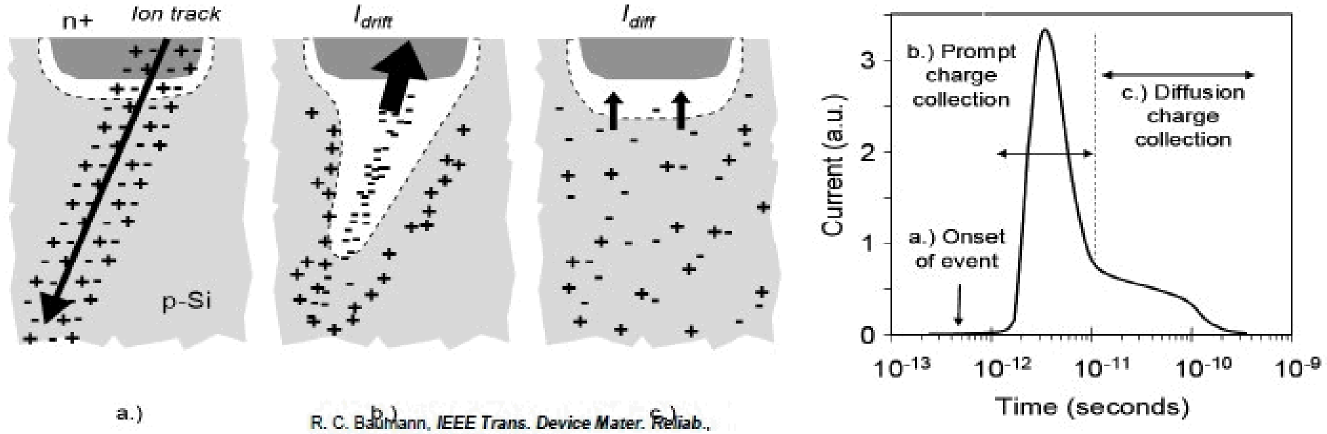
  - Electron-positron pair production



C. Claeys, E. Simoen; "Radiation Effects in Advanced Semiconductor Materials and Devices; Springer-Verlag; 2002

Single Event Effects (SEEs) can be Caused by a Single Particle

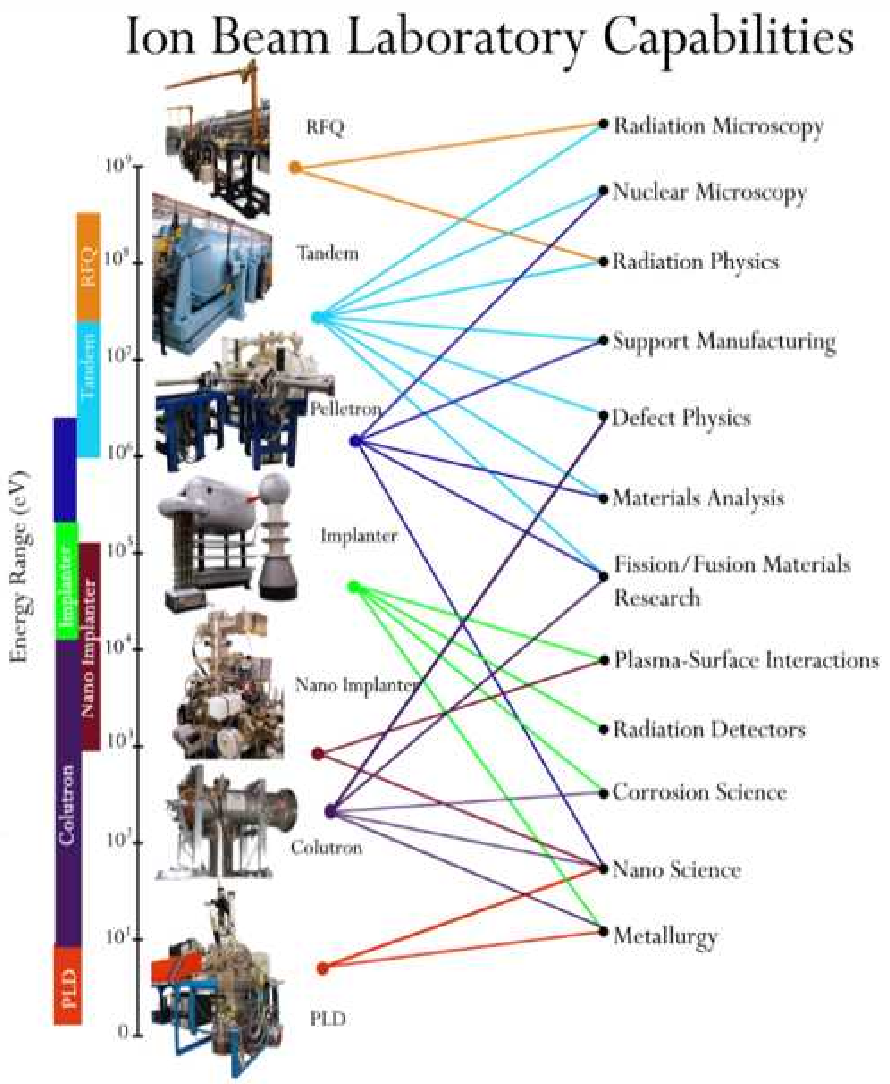
- A single high-energy particle strikes a device
- An *ionized track* is generated
- Electrons are swept toward the positive node
- The effect is a function of the device's bias state and the energy of the ion
  - Single Event Upset (SEU)
  - Single Event Latch-up (SEL)
  - Single Event Burnout (SEB)



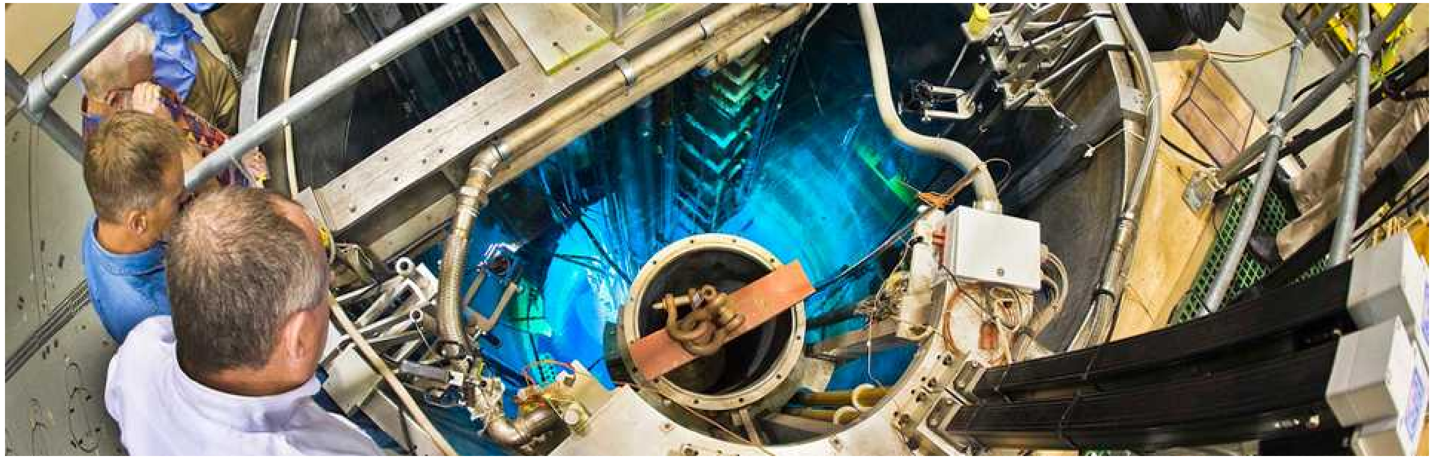
R. C. Baumann, *IEEE Trans. Device Mater. Reliab.*, vol. 5(3), p. 305-316, Sept. 2005

Sandia Facilities Enable the Testing of Various Radiation Effects and Damage Modes: Ion Beam Lab

- Sandia's ***Ion Beam Lab (IBL)*** is a state-of-the-art facility using ion and electron accelerators to study and modify materials systems.
- IBL has several capabilities ranging from advanced microscopy methods to material modification
- Alteration of the structure through ion beam interactions
  - Implantation of dopants
  - Sputtering of material
  - Decomposition of gasses



Sandia Facilities Enable the Testing of Various Radiation Effects and Damage Modes: Annular Core Research Reactor



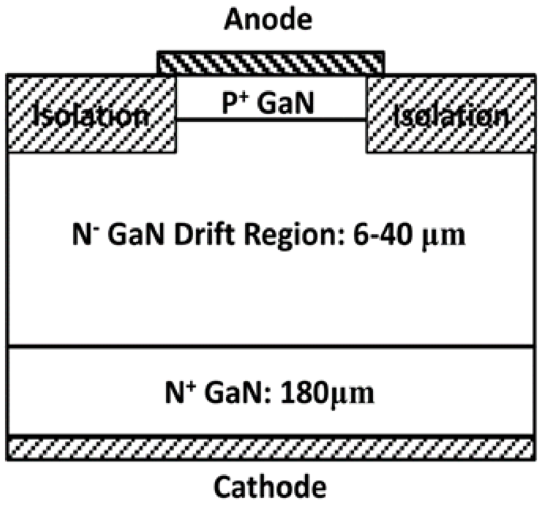
- The ***Annular Core Research Reactor (ACRR)*** facility can subject various test objects to a mixed photon and neutron irradiation environment
  - Capable of very rapid pulse rate
  - Long-term, steady-state rate
- Tests commonly done on
  - Electronic circuit boards and components (e.g., transistors and diodes)
  - Neutron or gamma active dosimetry devices (e.g., neutron/gamma detectors and semiconductor devices)
- Useful for simulating displacement damage in solar cells for satellites
  - Neutrons simulate a high fluence of protons typical of satellite orbits

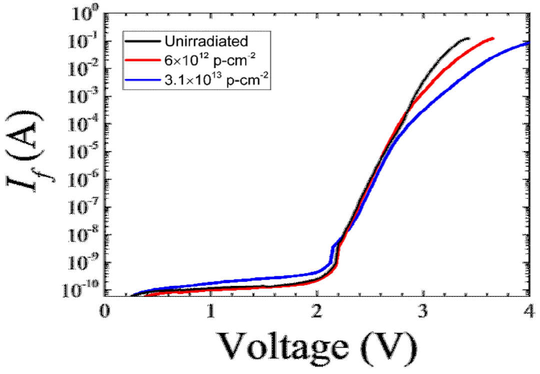
Sandia Facilities Enable the Testing of Various Radiation Effects and Damage Modes: Gamma Irradiation Facility

- The ***Gamma Irradiation Facility (GIF)*** simulates nuclear radiation environments for materials and component testing.
  - GIF can produce a wide range of gamma radiation environments (from 10^{-3} to over 10^{3} rad/second) using cobalt-60 sources
  - GIF can irradiate objects as small as electronic components and as large as a satellite
- GIF is for:
  - Testing for electronic-component hardness
  - Materials-properties testing
  - Investigations of various physical and chemical processes
  - Testing and radiation certification of satellite and weapons system electronic components
  - Investigations of radiation damage to materials.

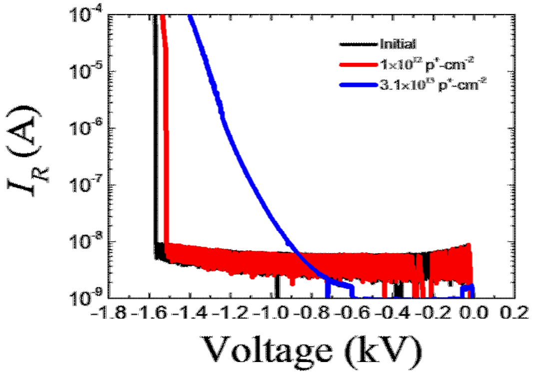
Example of Radiation Effects in a WBG Device: Proton and Neutron Irradiation of GaN PiN Diodes

Vertical GaN P-i-N diodes were evaluated before and after irradiation with neutrons and protons

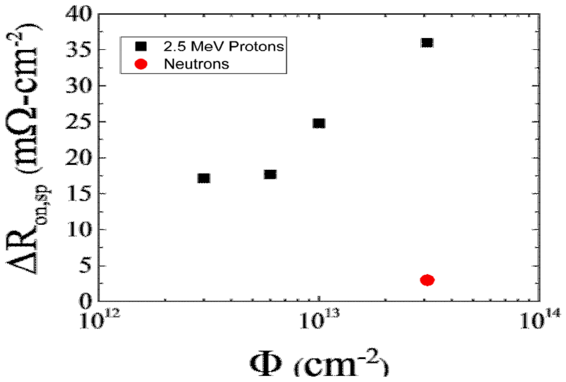




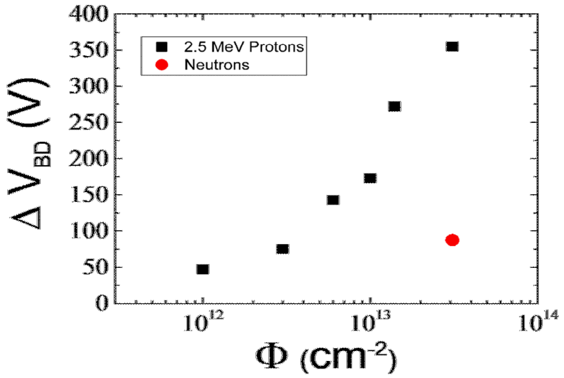
- Irradiation with protons leads to increase in generation current and higher resistivity in *on*-state characteristics



- Irradiation leads to increased leakage and decreased V_{BD}
- Softer reverse breakdown characteristics



- Increase in $R_{on,sp}$ results from higher series resistance from scattering centers in the *n*- drift region and *p*-GaN layers

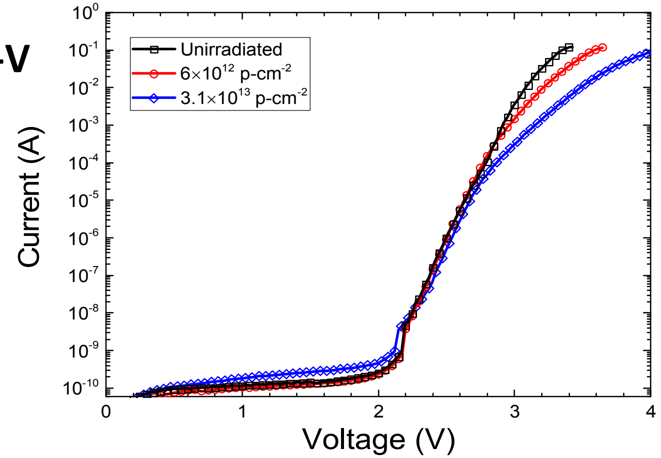


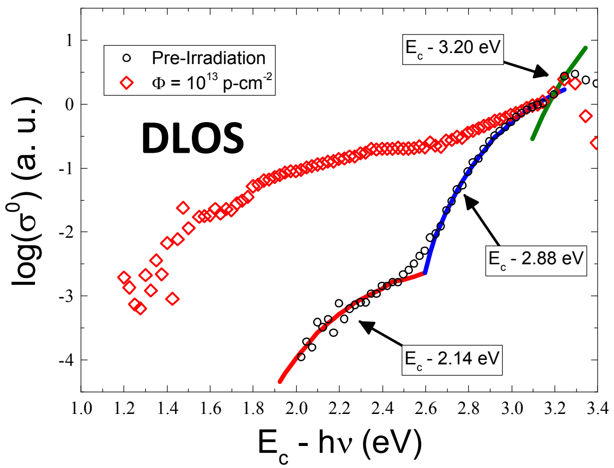
- V_{BD} trends following exposure to protons and neutrons show similar trends
- Compensation of holes in *p*-GaN field rings likely causes reduced V_{BD}

M. P. King et al., IEEE TNS 62(6), 2912 (2015)

Change in Deep Level Spectra Correlates with Change in Electrical Characteristics

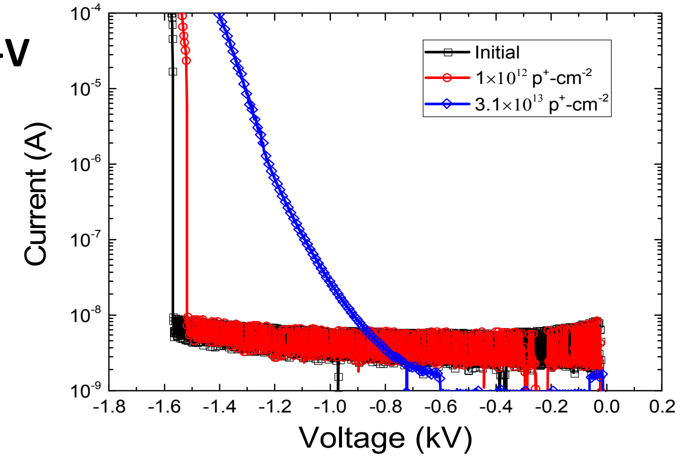
Forward I-V

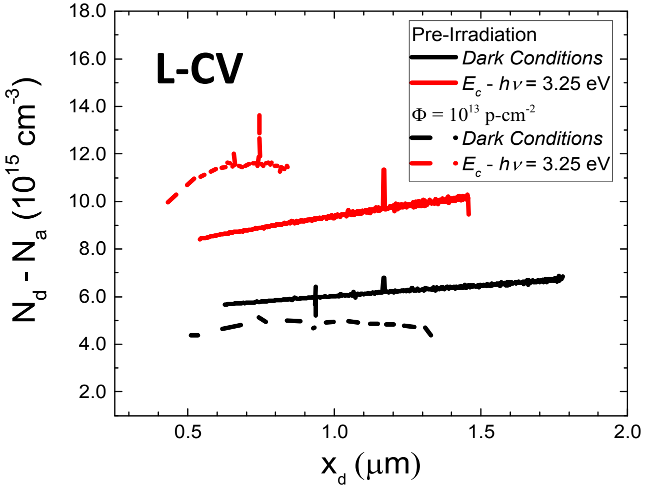




Deep level energies

Reverse I-V



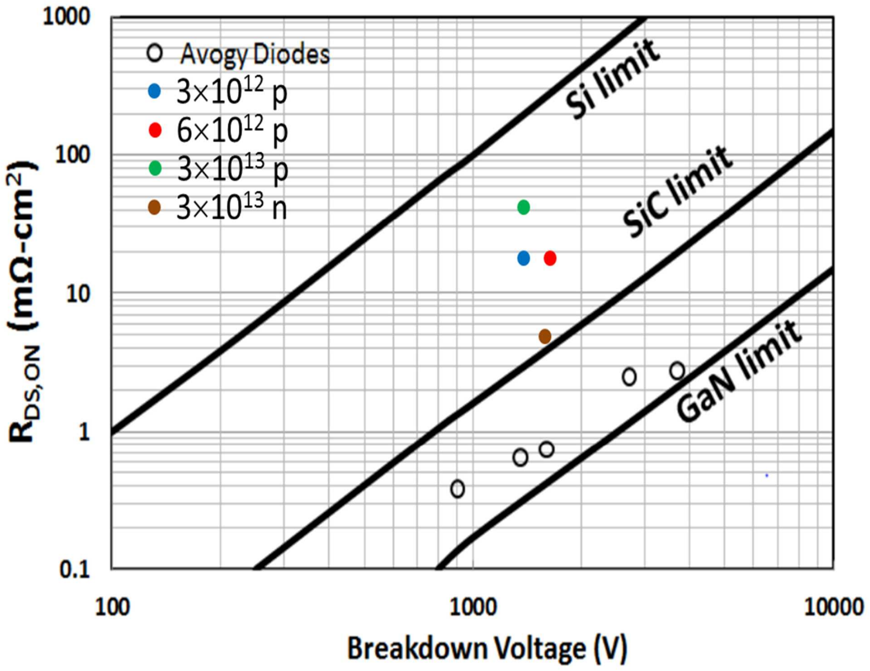


Deep level concentrations

M. P. King et al., IEEE TNS 62(6), 2912 (2015)

Irradiated GaN Devices Retain Good Performance

- Unipolar Figure of Merit (UFOM) is a well-established standard for comparison of devices
  - Ideal device would have high V_{BD} and low $R_{on,sp}$ aligning far to the bottom right of the UFOM
- Wide-bandgap materials exceed the performance of Si-based devices
- Irradiated GaN devices still out-perform Si devices



Unipolar FOM = $V_B^2/R_{on,sp} = \varepsilon \mu_n E_C^3/4$

Summary

- WBG materials improve the SWaP of power converters
- They may also improve the resiliency of power converters in radiation environments, such as outer space
- Different types of radiation damage may occur
  - Displacement damage
  - Transmutation
  - Ionization
  - Single events
- Test facilities are utilized to evaluate these types of damage
- Preliminary testing on GaN diodes has suggested good robustness