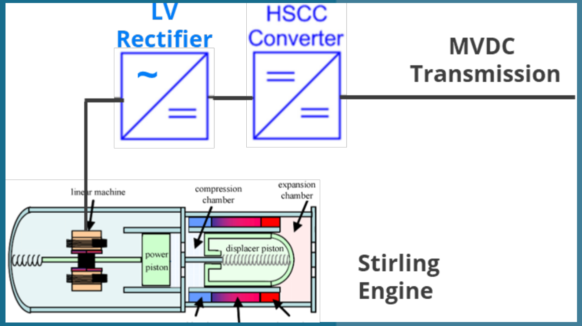
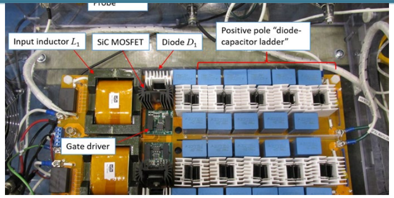
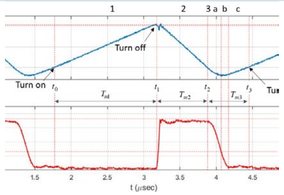
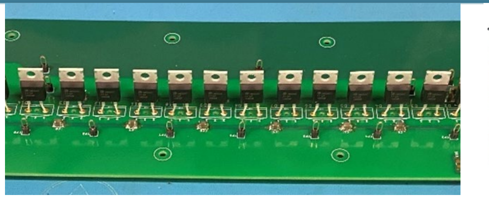
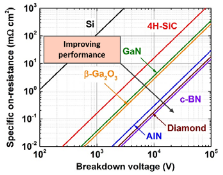
Hybrid Switched Capacitor Converter with WBG Devices for Medium Voltage DC Transmission in Space Environments











Jason C. Neely and Bob Kaplar

LSIC Surface Power Telecon, February 22, 2024

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

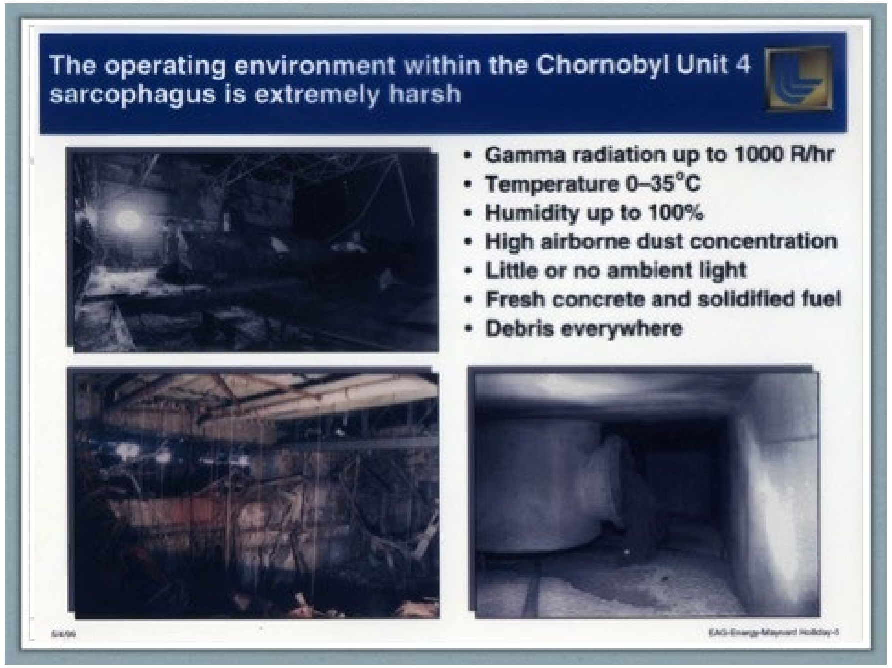
SAND2024-01926PE

Rad-Resilient Power Electronics May Enable Improved Nuclear Disaster Response

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

Dai-ichi Reactor Buildings – Post Incident

Work at Dai-ichi – Post Incident



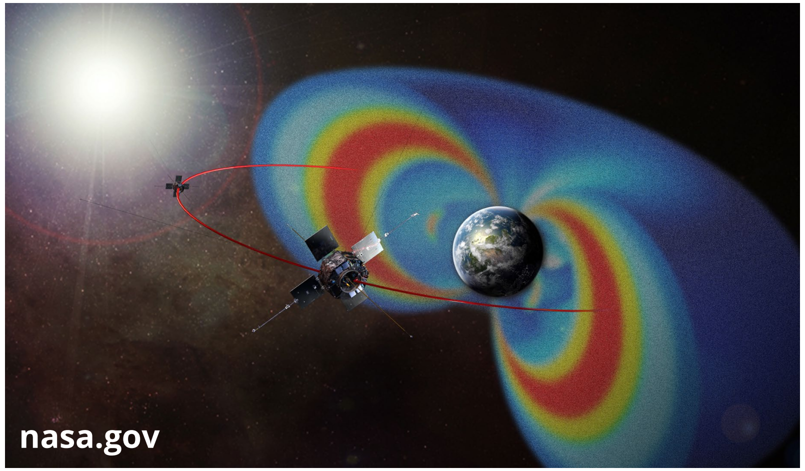
The operating environment within the Chornobyl Unit 4 sarcophagus is extremely harsh

- Gamma radiation up to 1000 R/hr
- Temperature 0–35°C
- Humidity up to 100%
- High airborne dust concentration
- Little or no ambient light
- Fresh concrete and solidified fuel
- Debris everywhere

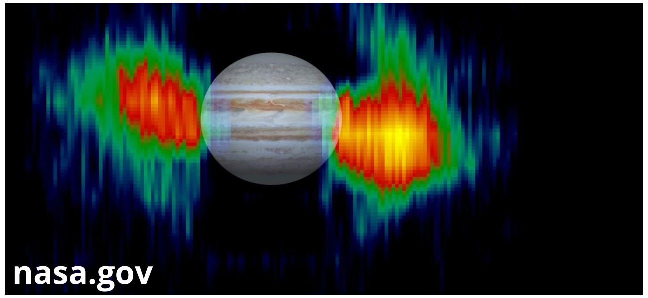
EAG-Energy-Maynard Holliday-5

Rad-Resilient Power Electronics May Enable Extended Space Missions

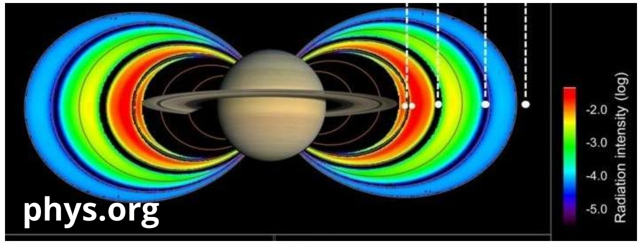
- Energetic charged particles from solar wind and cosmic rays are present in the solar system
- High concentrations of charged particles exist around Earth
  - Inner Van Allen belt: 1,000 – 6,000 km above Earth
    - 100s of keV electrons
    - Up to 100 MeV protons
  - Outer Van Allen belt: 13,000 – 60,000 km above Earth
    - 100 keV – 10 MeV electrons
    - Protons and ions (alpha particles and heavy 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, e.g. Jupiter and Saturn
- Radiation exposure of space craft components influences design, flight plans, and mission time



nasa.gov



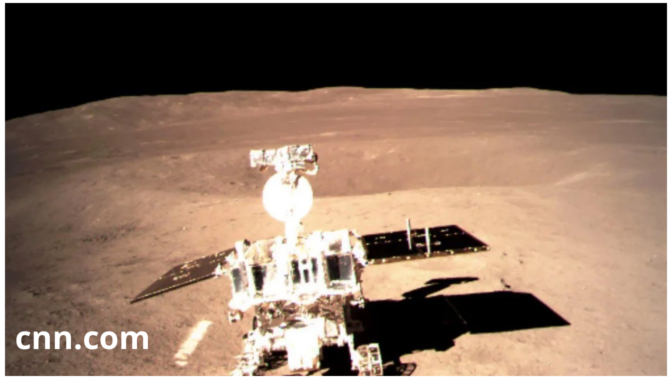
nasa.gov

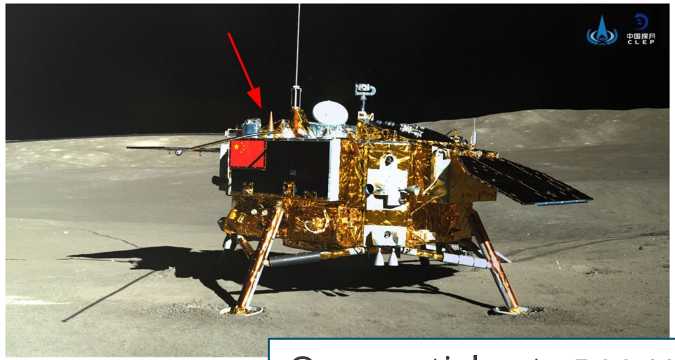


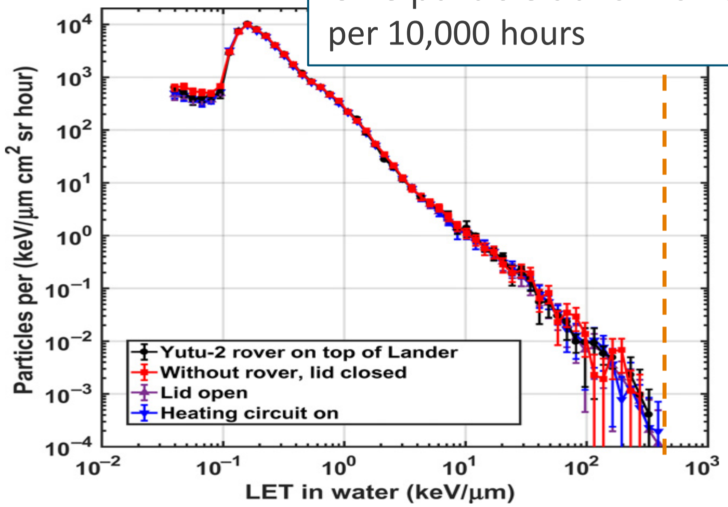
phys.org

Rad-Resilient Power Electronics May Enable Extended Space Missions

- “When the next astronaut to reach the moon walks on the lunar surface in 2024, she’ll face radiation levels 200 times higher than on Earth.”
- “The first systematically documented measurements of radiation on the moon were undertaken in January 2019 when China’s Chang’e 4 robotic spacecraft mission landed on the far side of the Moon, according to a new study in the journal Science Advances.”
- “[Radiation on the moon] includes galactic cosmic rays, sporadic solar particle events (when particles emitted by the sun become accelerated) and neutrons and gamma rays from interactions between space radiation and the lunar soil.”
- “’The radiation levels we measured on the Moon are about 200 times higher than on the surface of the Earth and 5 to 10 times higher than on a flight from New York to Frankfurt,…’”
- However, radiation can be substantially higher during a solar storm, which can include heavy elements such as iron





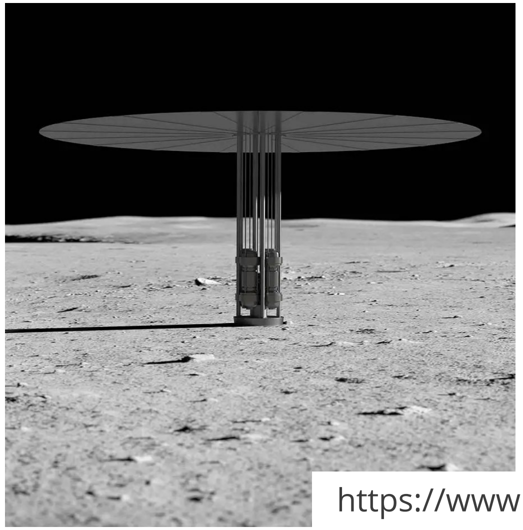


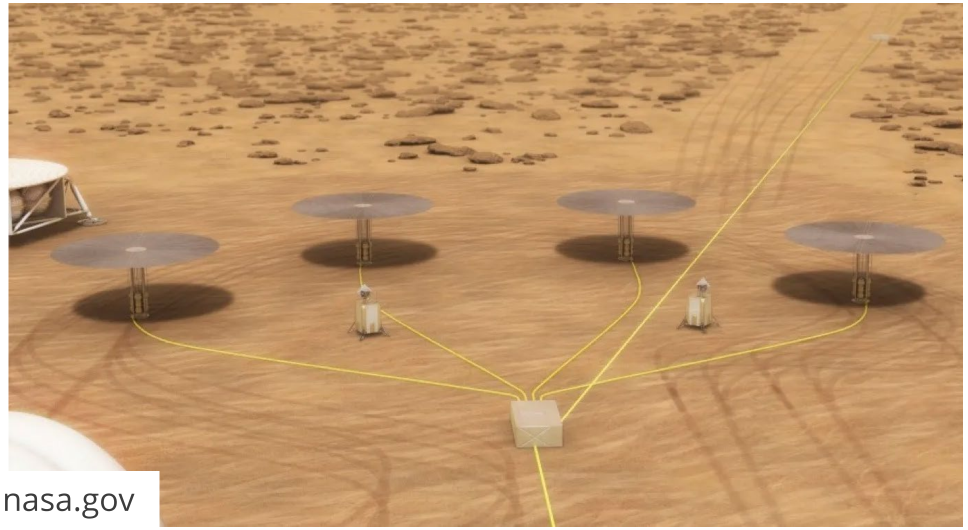
One particle at >5 MeV·cm^2/mg per 10,000 hours

https://www.cnn.com/2020/09/25/world/moon-radiation-astronauts-exposure-scn/index.html
https://www.science.org/doi/10.1126/sciadv.aaz1334

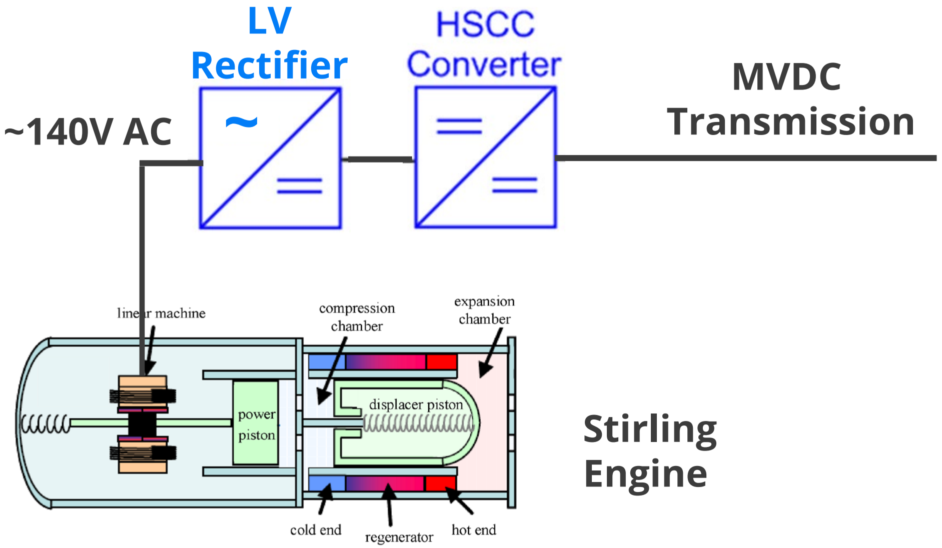
Rad-Resilient Medium Voltage Power Electronics Enable Power Transmission in Space

- Fission nuclear power systems may enable long-duration stays on the moon or Mars.
- Due to fission products (i.e. neutron, beta, gamma), reactors must be located a distance from people, and shielding is likely impractical
- Boosting the voltage enables more efficient transmission of power over distance and over smaller (lighter) conductors
- By converting the energy from the Stirling Converters to medium voltage direct current (MVDC) transmission losses are greatly reduced; e.g. at 5 kV, the 40 kilowatts can be transmitted 2 km over equivalent of 12 gauge wire with ~3.3% loss.
- Power devices used for conversion must be resilience to radiation at the higher voltages; the assembly must have high specific power; low weight for the power



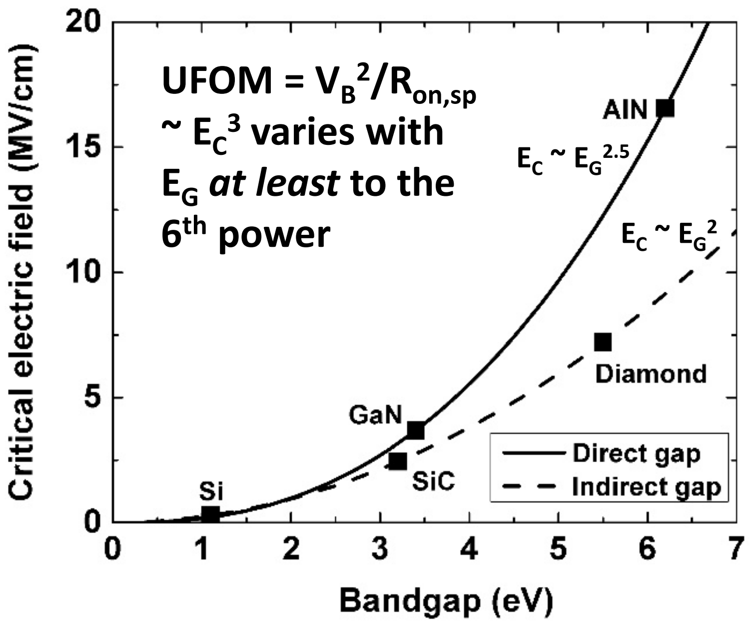


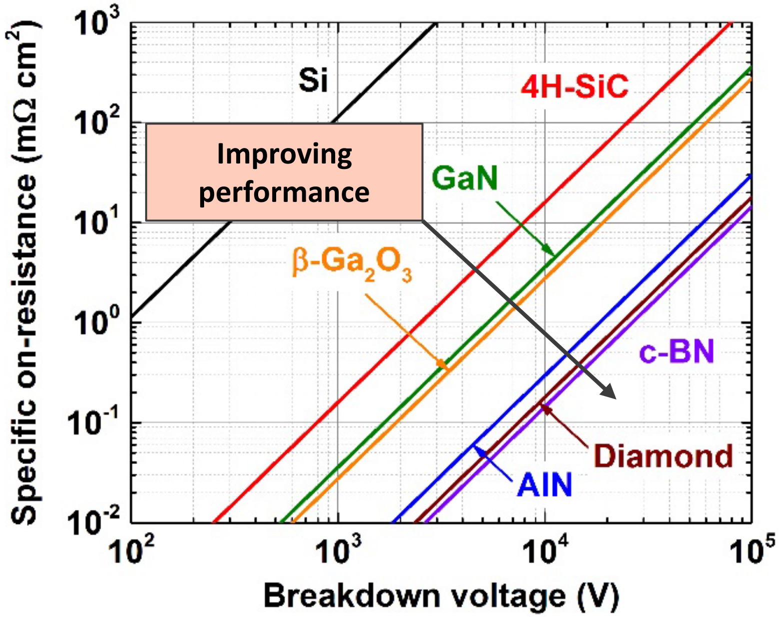
https://www.nasa.gov



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

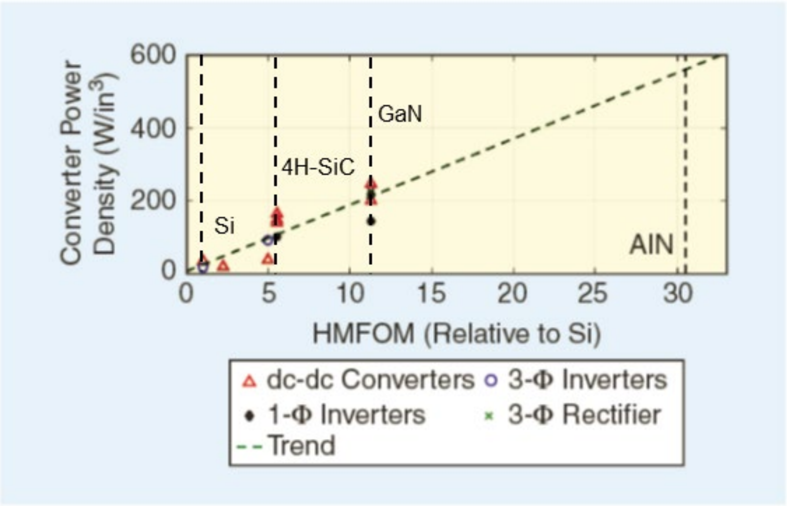




Unipolar FOM = $V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$

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

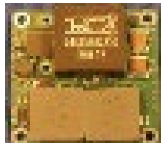
Semiconductor Material Properties Dictate System Volume and Weight



Huang Material FOM = $E_C\mu_n^{1/2}$

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

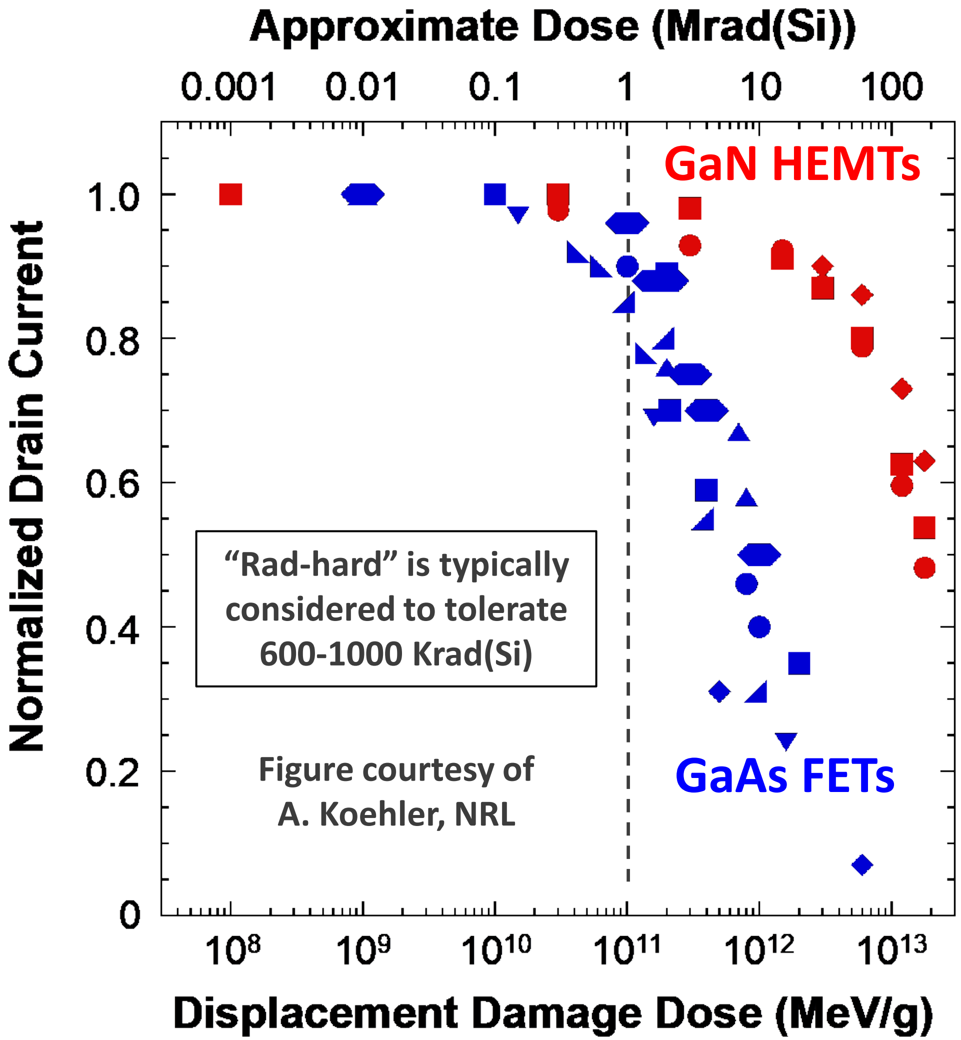
SNL GaN HEMT microinverter
400 W in 2.4 in^3 → 167 W/in^3



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

R. J. Kaplar, J. C. Neely, et al., *IEEE Power Electronics Magazine (March 2017)*

WBG and UWBG Devices Show Promise for Good Radiation Resistance



DDD = NIEL x Fluence

Data from literature includes:

- **450 keV, 1.8 MeV, and 40 MeV protons**
- **450 keV electrons**
- **1.5 MeV C^+ (carbon ions)**

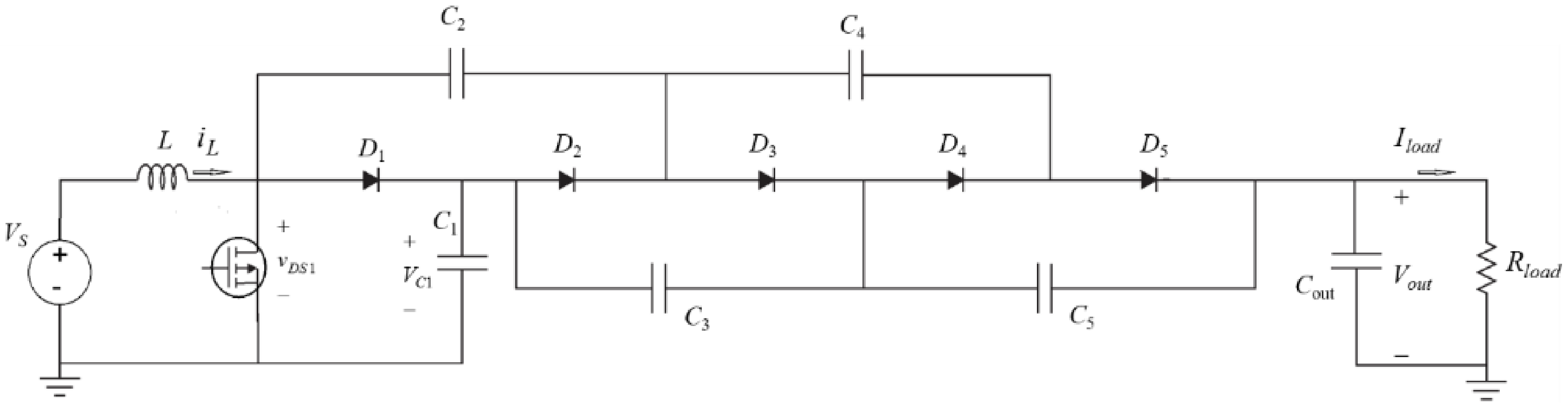
- Higher Displacement Damage Dose required to reach equivalent drain current degradation in GaN (3.4 eV) relative to GaAs (1.4 eV)
- Various factors may be responsible for this
  - Higher thresholds for atomic displacement
    - GaAs: E_d(Ga) = 9.8 eV, E_d(As) = 9.8 eV
    - GaN: E_d(Ga) = 20.5 eV, E_d(N) = 10.8 eV
  - Polarization doping in GaN compared to impurity doping in GaAs (determined to be dominant factor in this study)
- Number of e-h pairs is also reduced for ionizing radiation due to wider bandgap

D. D. Weaver et al,"On the Radiation Tolerance of AlGaN/GaN HEMTs," ECS J. Solid-State Sci. Tech. 5(7), Q208 (2016)

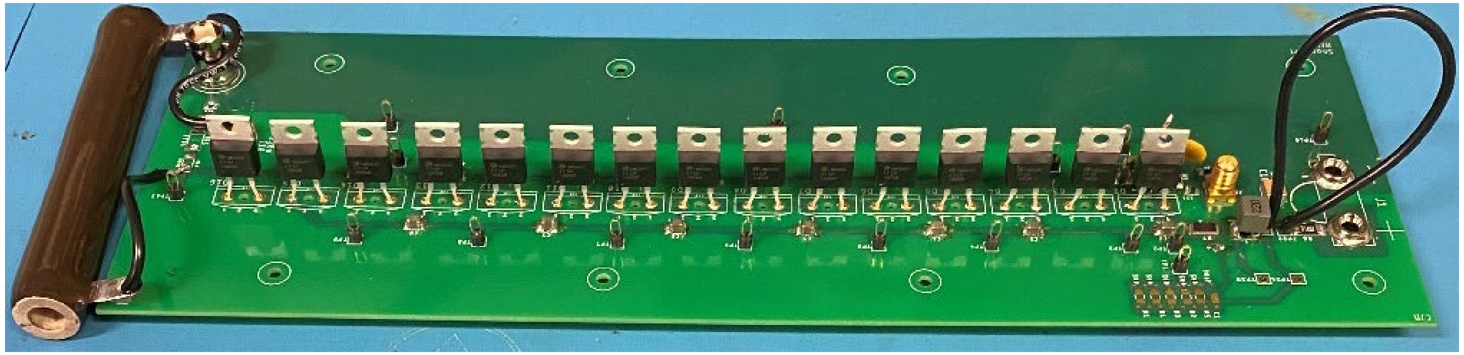
HSCC is a Multi-stage High Gain Boost Converter

- The HSCC includes a boost converter on the front end with N additional stages of capacitor-diode cells connected between the switch node and the output; circuit has one active switch
- Each stage is intended to contribute to the gain of the circuit by acting as a voltage mulitiplier stage. The circuit in general has one controlled switch, $2N+1$ diodes and $2N+2$ capacitors including an output capacitor.

2-stage “Unipolar” HSCC schematic



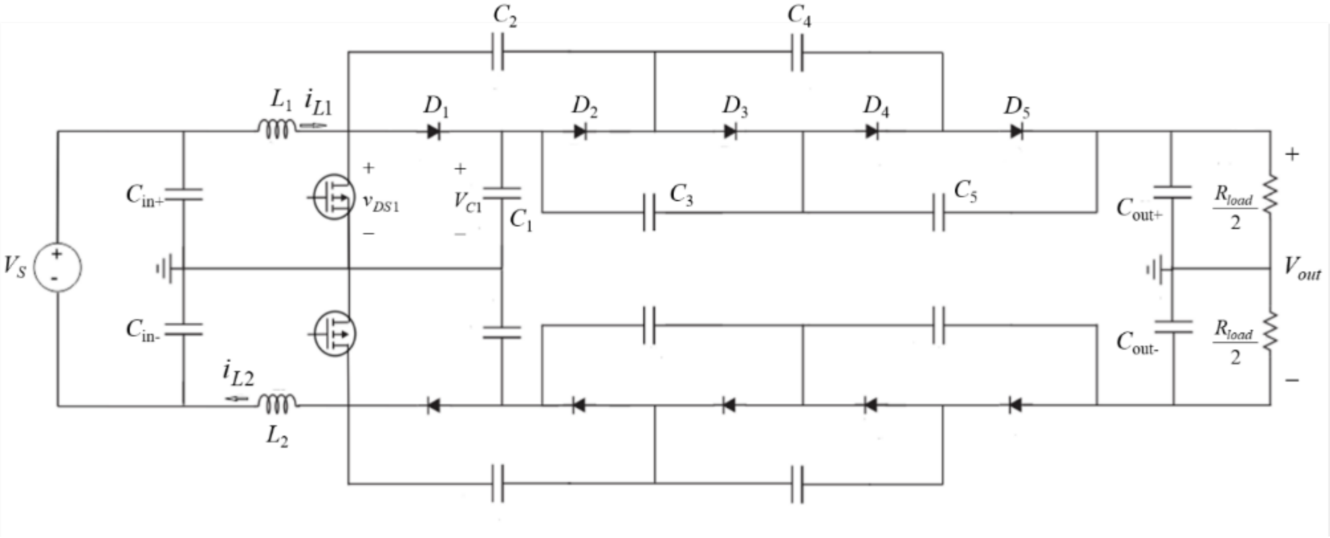
7-stage “Unipolar” HSCC prototype, demonstrated at 1kV



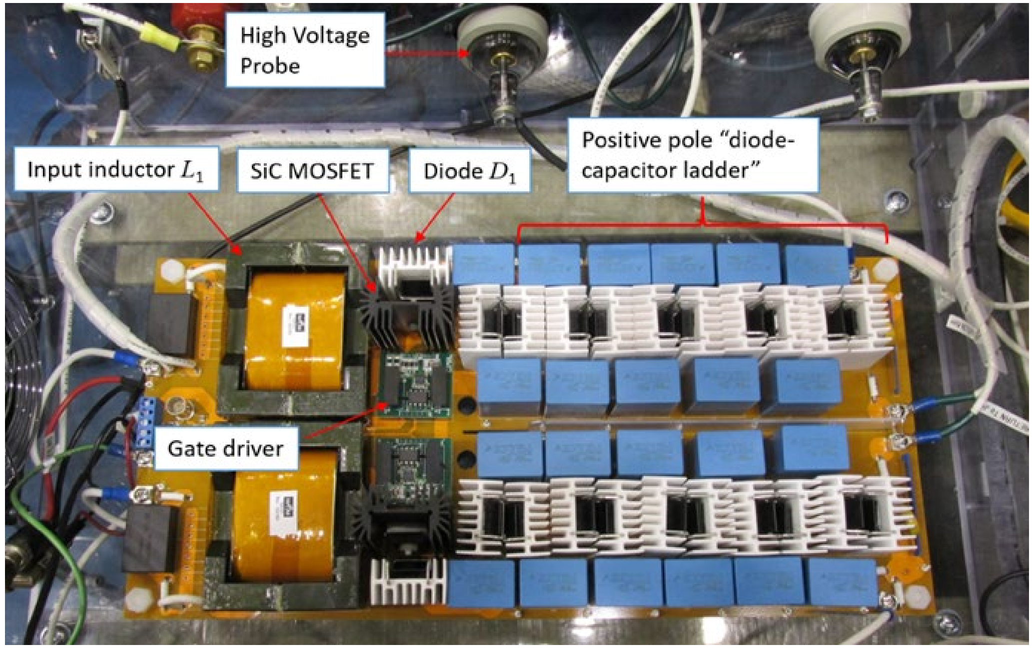
HSCC is a Multi-stage High Gain Boost Converter

- The HSCC may be modified to enable a “Bipolar” assembly, with positive and negative outputs; circuit has two active switches
- The motivation for the bipolar configuration is to enable higher gain converter applications without overstressing components or diminishing the converter efficiency.

2-stage “Bipolar” HSCC schematic

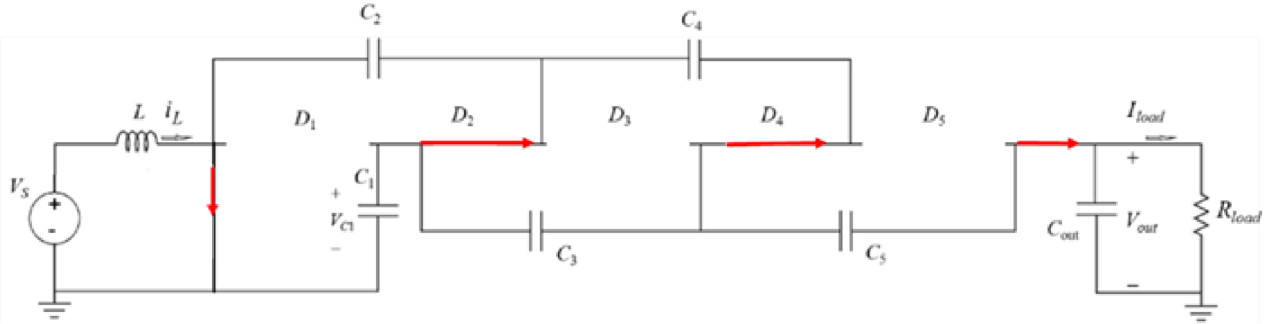


5-stage “Bipolar” HSCC prototype, demonstrated at 10kV (+/- 5kV) 8kW

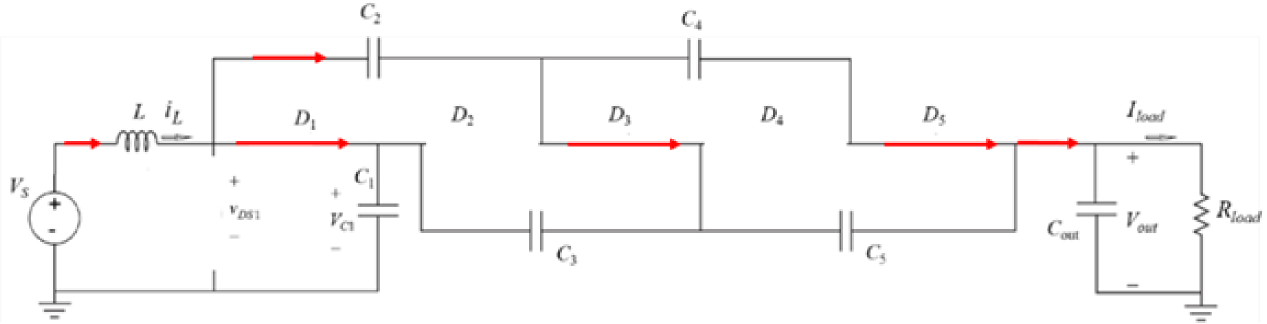


HSCC is a Multi-stage High Gain Boost Converter

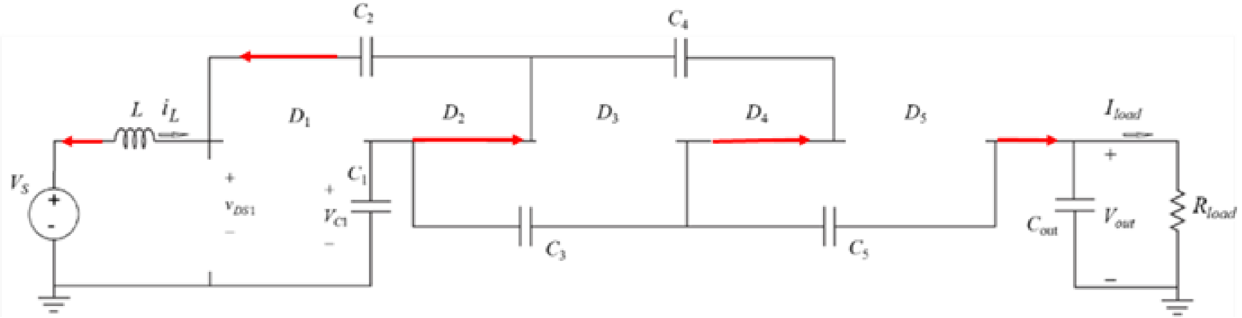
Mode 1: Switch *On*, $V_{C1} > V_{C2}$, $V_{C1} + V_{C3} > V_{C2} + V_{C4}$, D_2 and D_4 conducting



Mode 2: Switch *Off*, $i_L > 0$, D_1, D_3, and D_5 conducting

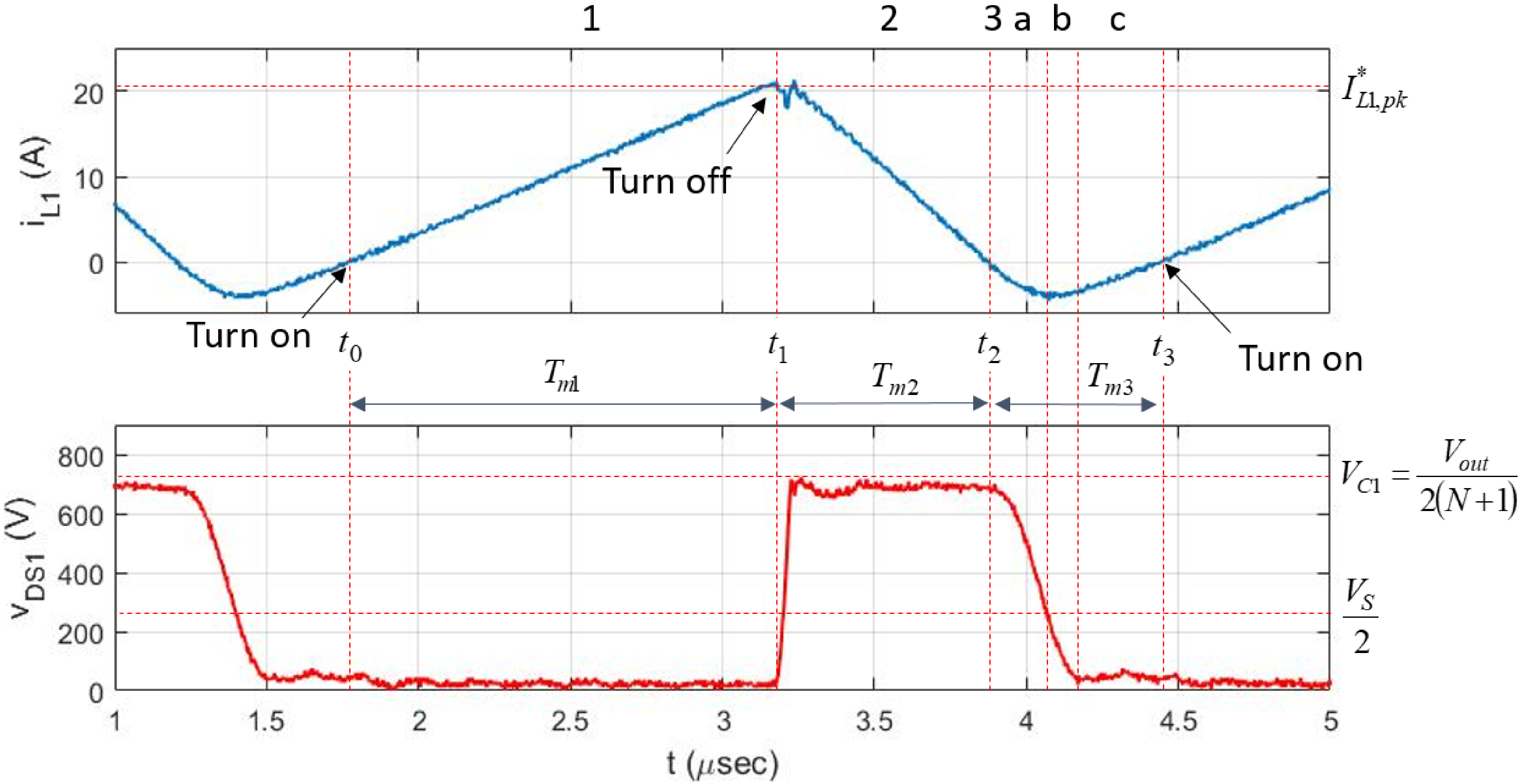


Mode 3: Switch *Off*, $i_L < 0$, D_2 and D_4 conducting



A Method to Regulate Input Power while Reducing Switching Loss was Developed

- MOSFET switches *on* as the inductor current is rising through the i_L=0 crossing
- MOSFET switches *off* when a reference peak current is reached
- Inductor current falls, drops below zero and then rises again

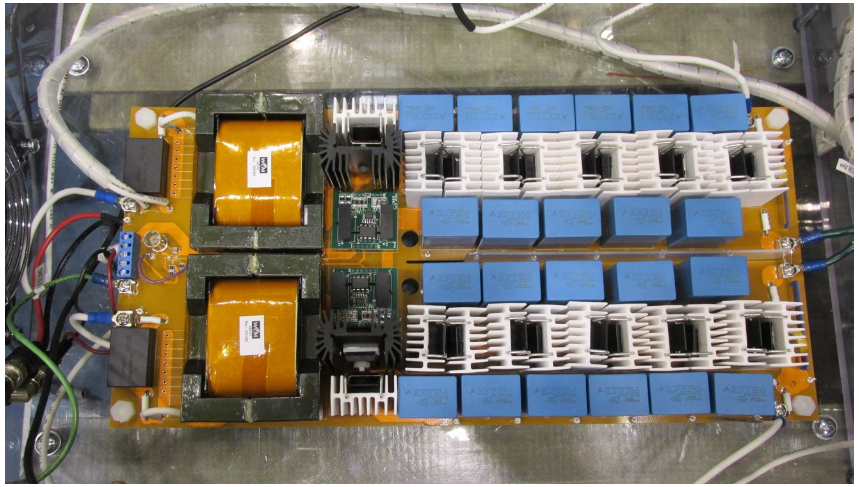


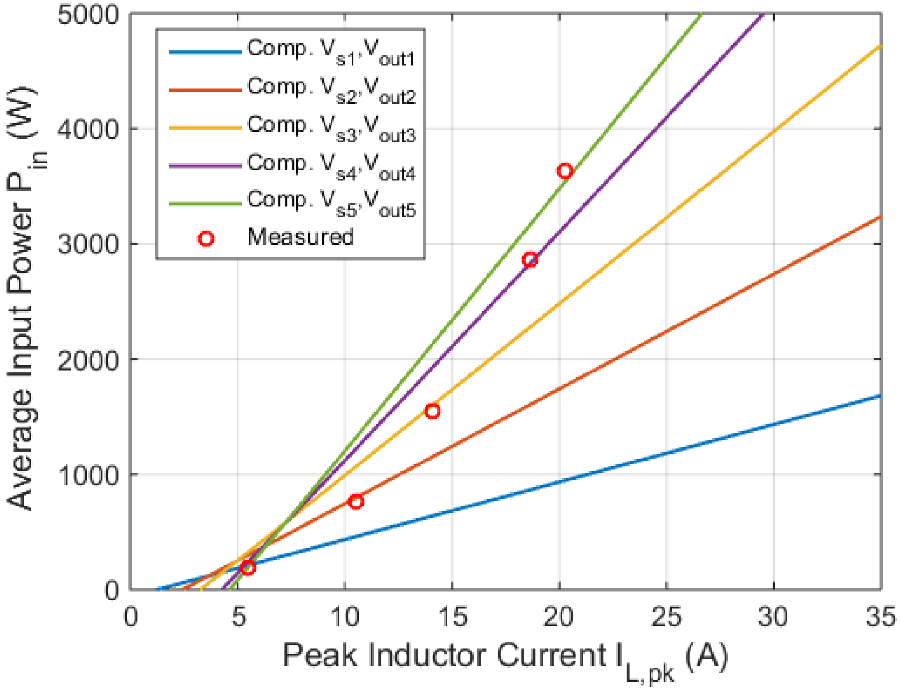
The Control Analysis was Validated in Bipolar Prototype

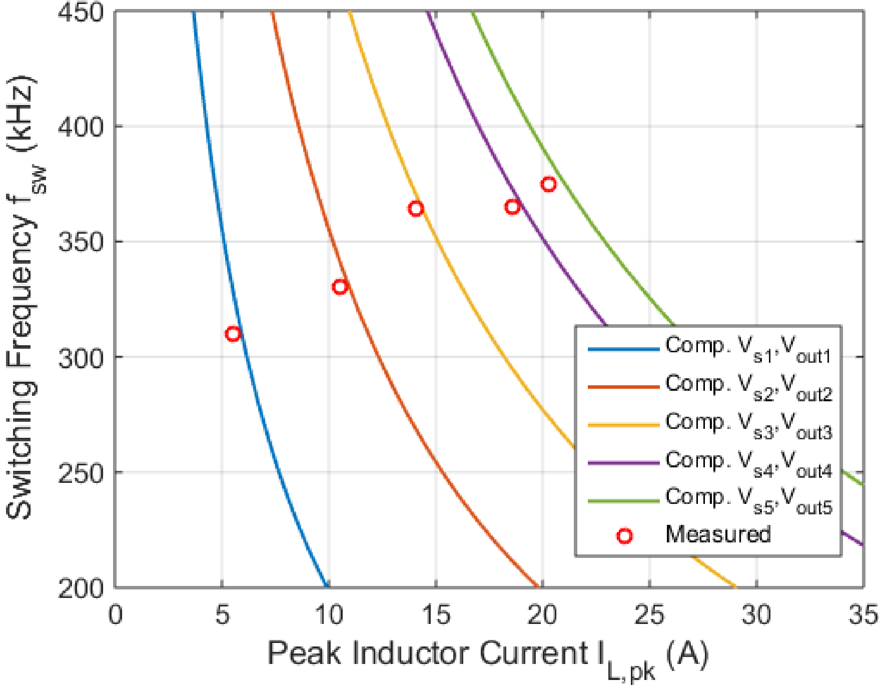
- Analytical prediction was compared to results from Prototype 2 testing

$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

$$f_{sw} = \frac{1}{\left(\frac{2L}{V_S} + \frac{2L(N+1)}{V_{out} - V_S(N+1)}\right) I_{L,pk} + \frac{1.375\tau_{CP}}{V_S(N+1)} V_{out}}$$

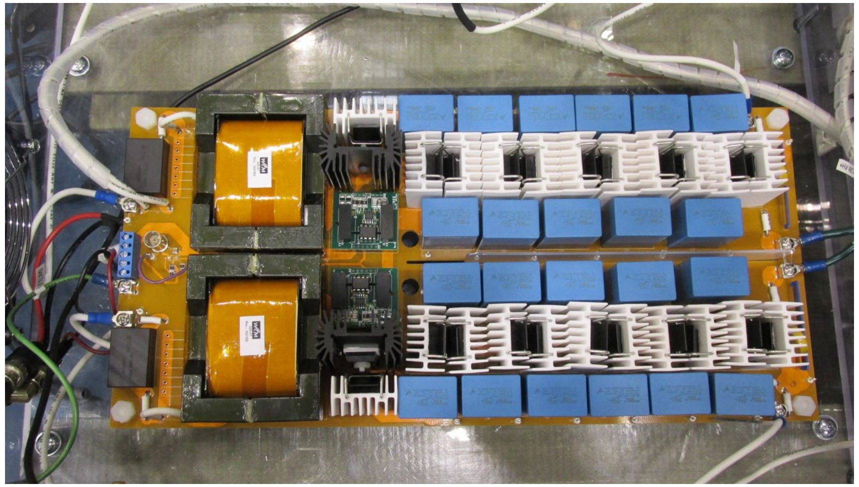






The Control Analysis was Validated in Bipolar Prototype

- Analytical prediction was compared to results from Prototype 2 testing



$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

$$f_{sw} = \frac{1}{\left(\frac{2L}{V_S} + \frac{2L(N+1)}{V_{out} - V_S(N+1)}\right) I_{L,pk} + \frac{1.375\tau_{CP}}{V_S(N+1)} V_{out}}$$

Exp.	V_S (V)	$I_{L,pk}$ (A)	V_{out} (V)	P_{in} (W)	Eff (%)	Gain	f_{sw} (kHz)	$I_{L,min}$ (A)
1	100	5.52	2142	190.4	97.88	21.44	310	-1.44
2	200	10.5	4247	766.2	97.56	21.26	330	-2.56
3	300	14.1	5911	1543.8	97.64	19.72	364	-3.12
4	400	18.6	7788	2855.6	97.63	19.47	365	-3.60
5	460	20.3	8630	3632.6	96.93	18.77	375	-3.92

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 flux ϕ is specified in units of particles/s·cm^2
- Particle fluence Φ is the flux integrated over total exposure time, specified in units of particles/cm^2
- The dose is the energy deposited per gram of material
  - 1 rad = 0.01 J/kg = 6.24x10^{13} eV/g
  - Dose rate is the deposited dose per unit exposure time, specified in units of rad(mat)/s

phys.org

brickshelf.com

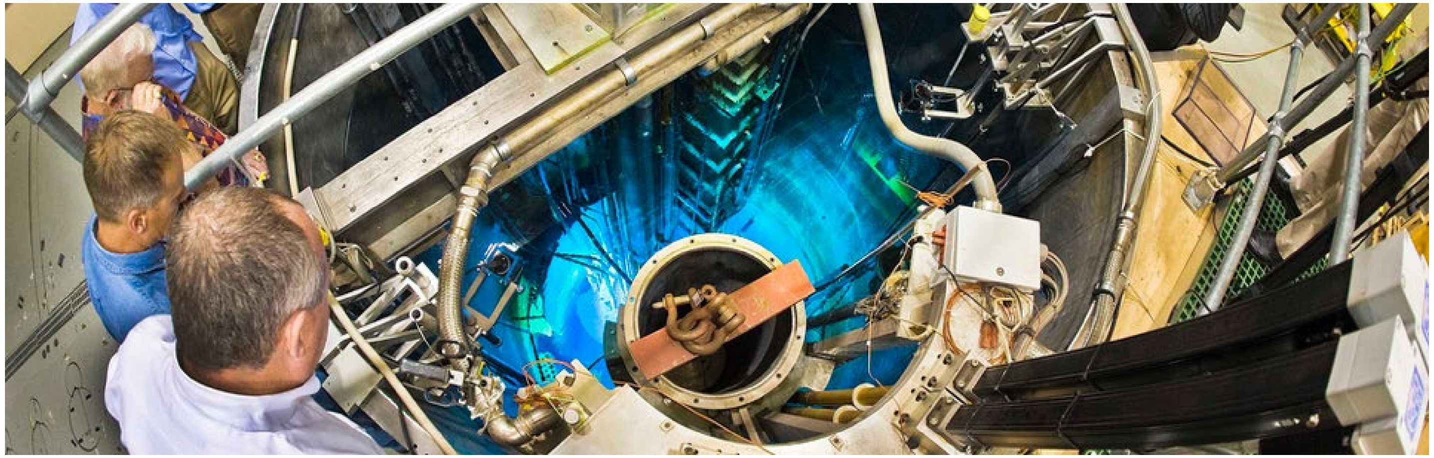
custombricks.net

Sandia Facilities Test Radiation Effects and Damage Modes: Gamma Irradiation Facility

- The *Gamma Irradiation Facility (GIF)* simulates gamma radiation environments for materials and component testing
  - GIF produces a wide range of gamma radiation environments (from 10^{-3} to over 10^{3} rad/s) using cobalt-60 sources
  - GIF can irradiate objects as small as electronic components and as large as a satellite

- GIF is used for:
  - Testing for electronic-component hardness
  - Materials-properties testing
  - Investigations of various physical and chemical processes
  - Testing and radiation certification of satellite system electronic components
  - Investigations of radiation damage to materials

Sandia Facilities Test Radiation Effects and Damage Modes: Annular Core Research Reactor



- The *Annular Core Research Reactor (ACRR)* can subject test objects to a mixed photon and neutron irradiation environment
  - Capable of delivering short pulses
  - Also capable of long-term, steady-state tests

- 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)

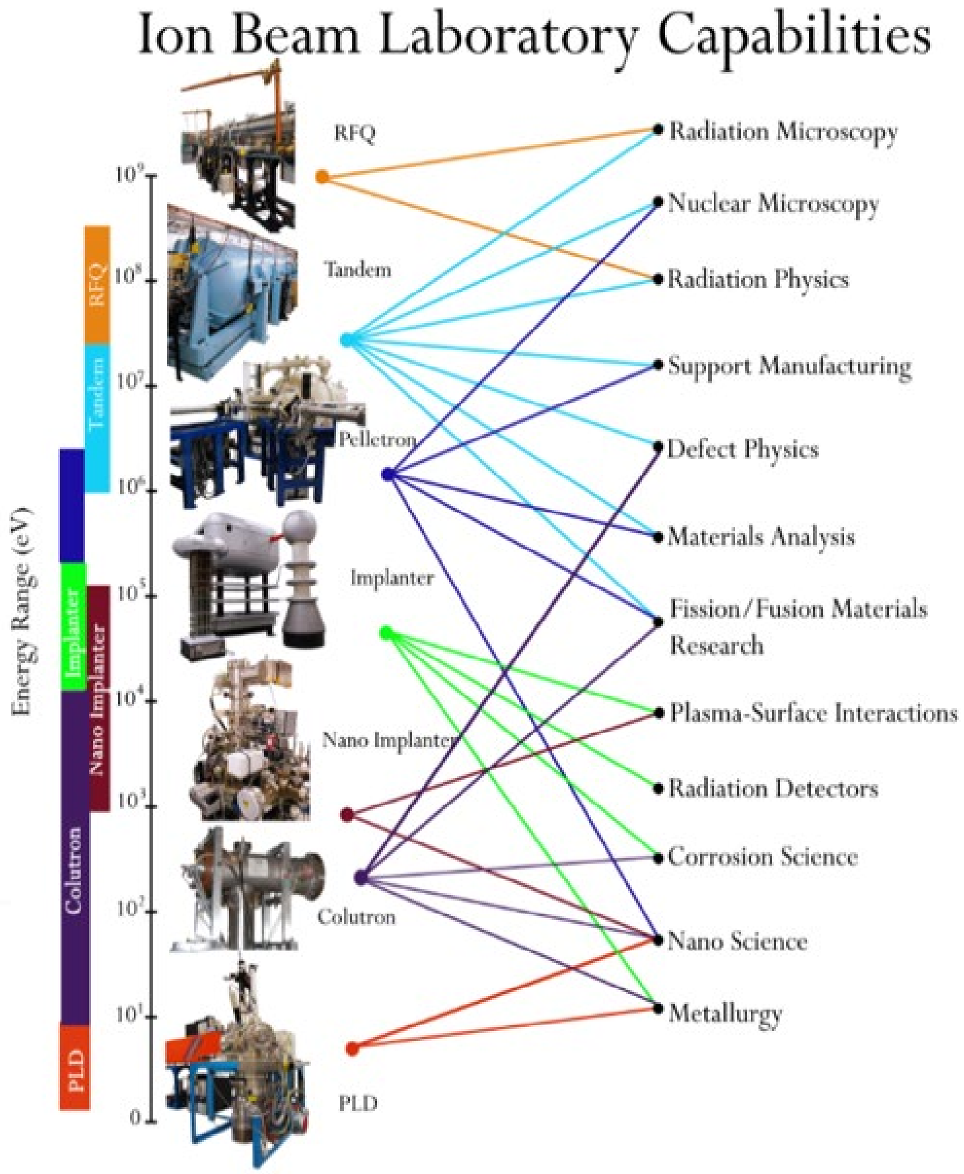
- Useful for simulating displacement damage in solar cells for satellites
  - Neutrons simulate a high fluence of protons typical of satellite orbits

Sandia Facilities Test 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 by ion irradiation

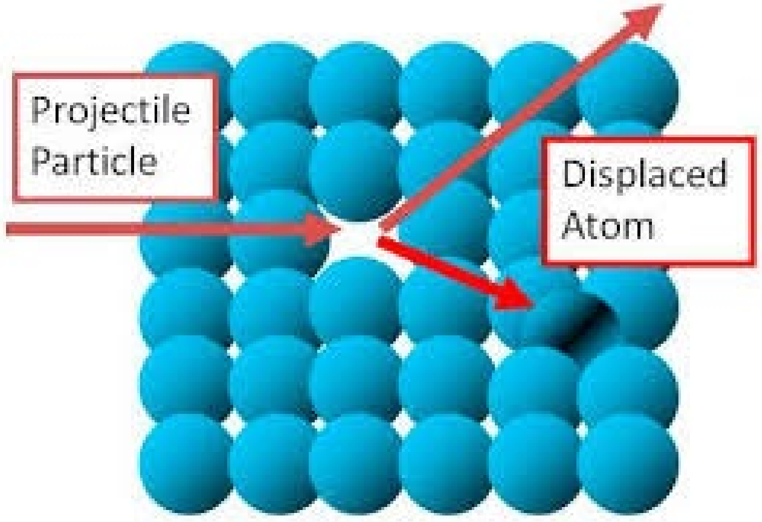
- ➢IBL has several capabilities ranging from advanced microscopy methods to material modification

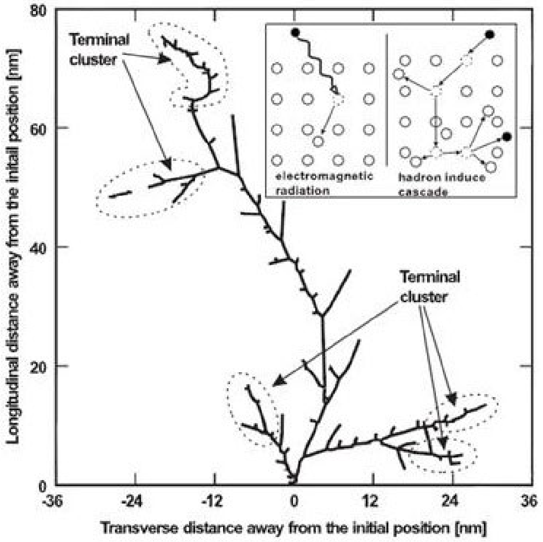
- ➢Alteration of the structure through ion beam interactions includes:
  - Implantation of dopants
  - Sputtering of material
  - Decomposition of gases



Displacement Damage Involves a Change to the Semiconductor Lattice

- First main damage mode
- Caused by a nuclear collision that knocks an atom from its lattice site
    - Changes the positions of atoms in a lattice
    - Damage cascades can occur
- Typically caused by particles with large mass
    - Neutrons
    - Protons
    - Alpha particles
    - Heavy ions
- Can also be caused by very high energy photons
- Damage is measured by Non-Ionizing Energy Loss (NIEL)
    - Non-ionizing energy deposited per unit length per unit density
    - Specified in units of eV·cm^2/g



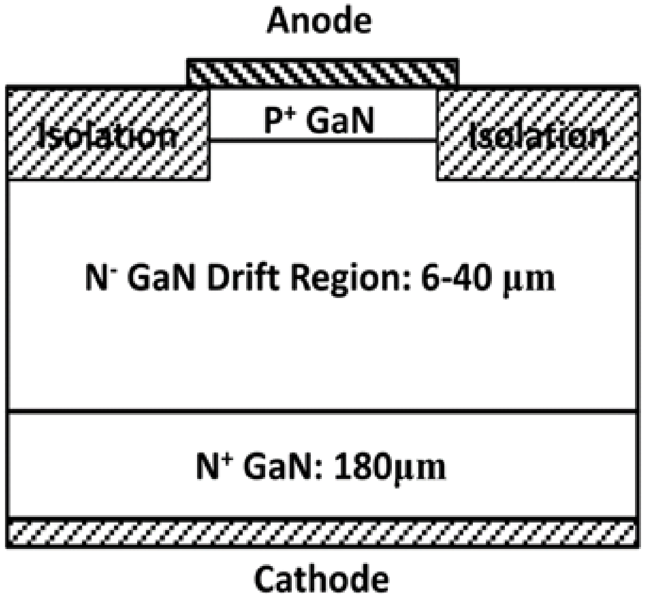


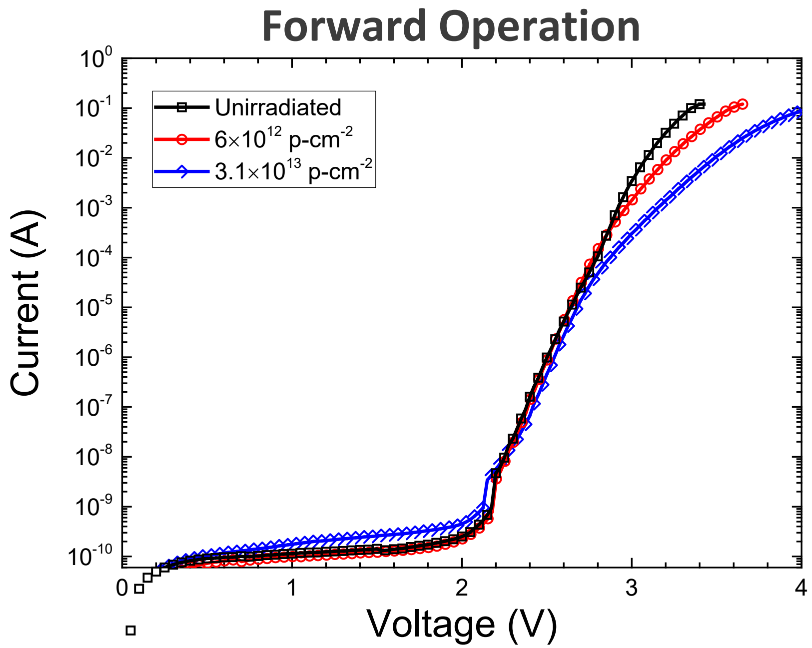
Displacement damage may cascade in a complex pattern

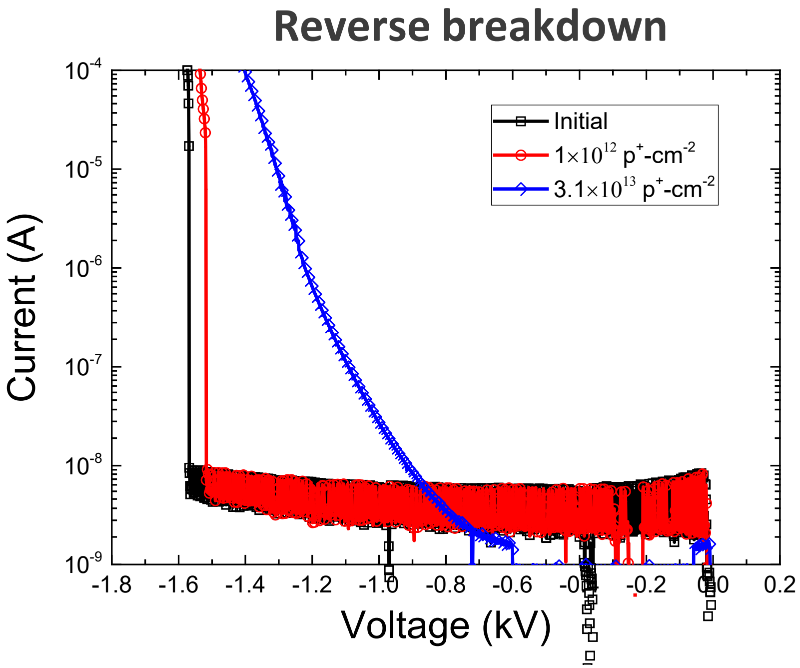
C. Claeys and E. Simoen, “Radiation Effects in Advanced Semiconductor Materials and Devices,” Springer-Verlag (2002)

Proton and Neutron Irradiation of Vertical GaN PiN Diodes

Vertical GaN PiN diodes were evaluated before and after irradiation with 2.5 MeV protons and 1 MeV neutrons




Forward Operation

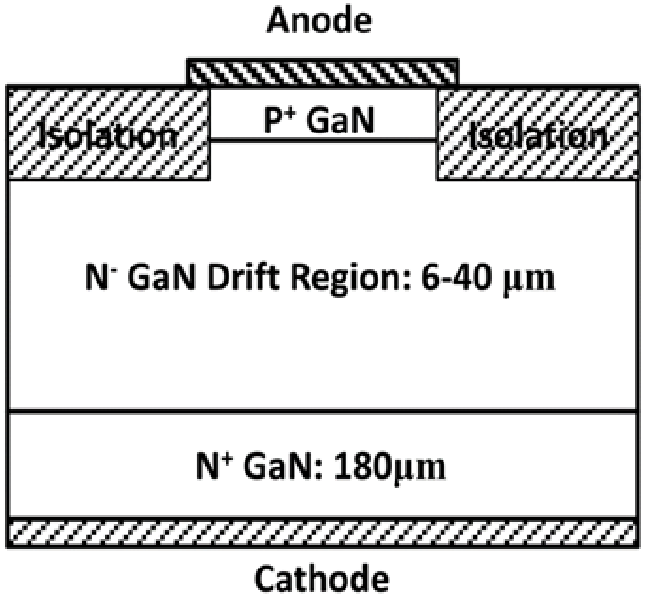

Reverse breakdown

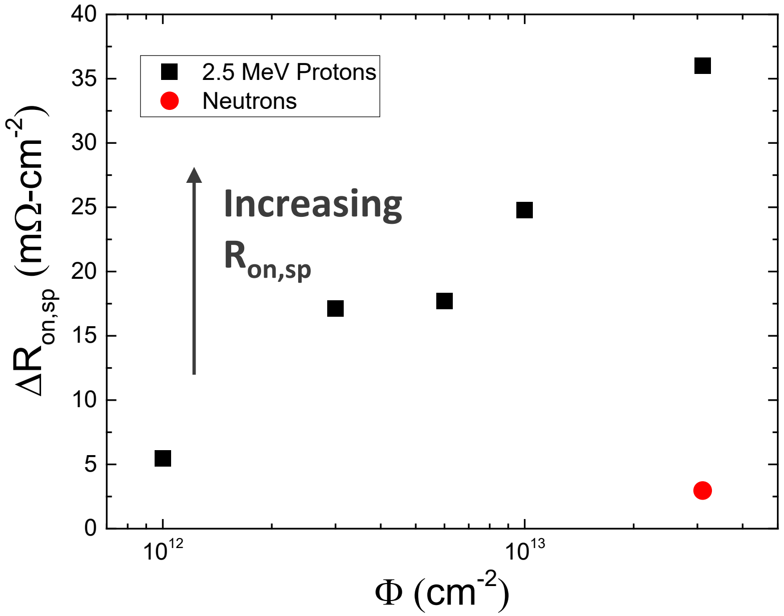
- Unirradiated, $6\text{x}10^{12}$ cm^{-2}, and $3.1\text{x}10^{13}$ cm^{-2} proton fluences compared
- Proton irradiation results in degradation to forward and reverse I-V characteristics
- Degradation is more severe at higher fluence (qualitative change in breakdown)

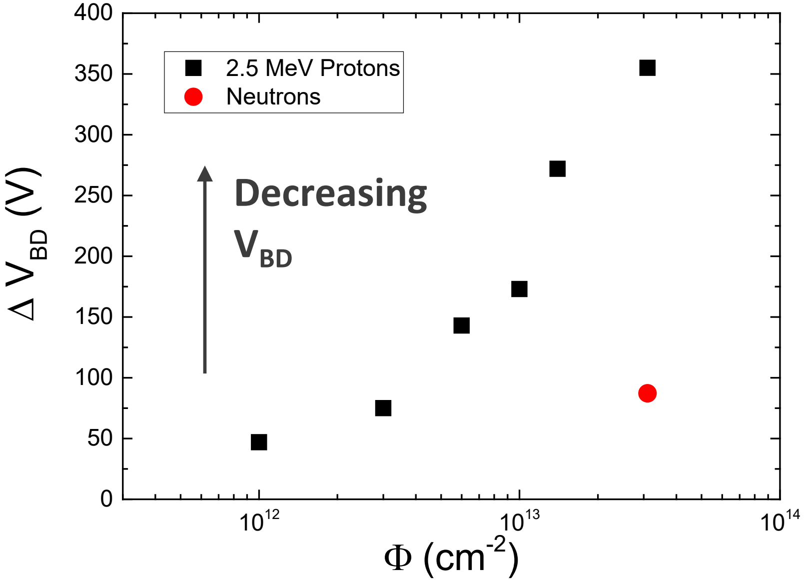
M. P. King et al., IEEE TNS 62(6), 2912 (2015)

Proton and Neutron Irradiation of Vertical GaN PiN Diodes

Vertical GaN PiN diodes were evaluated before and after irradiation with 2.5 MeV protons and 1 MeV neutrons



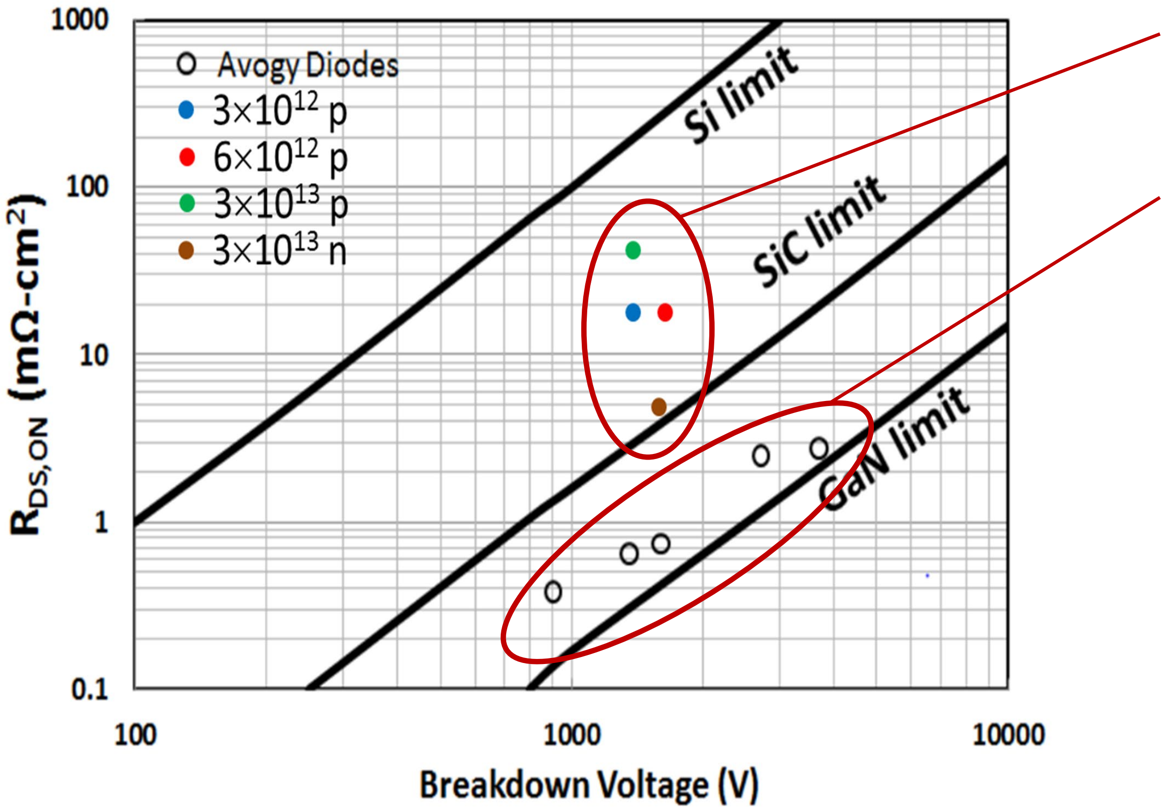




- Both $R_{on,sp}$ and V_{BD} show monotonically increasing degradation with increasing proton fluence
- Neutron damage is not as severe for equivalent fluence
- Performance hard to quantify at higher fluence due to qualitative change in I-V characteristics

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

Irradiated Vertical GaN Diodes Retain Relatively Good Performance



Irradiated diodes

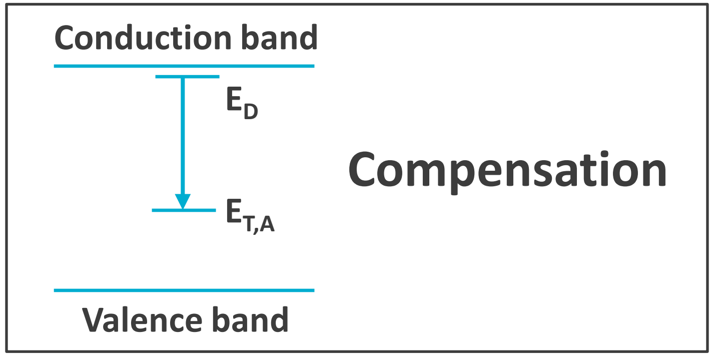
Fresh diodes

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

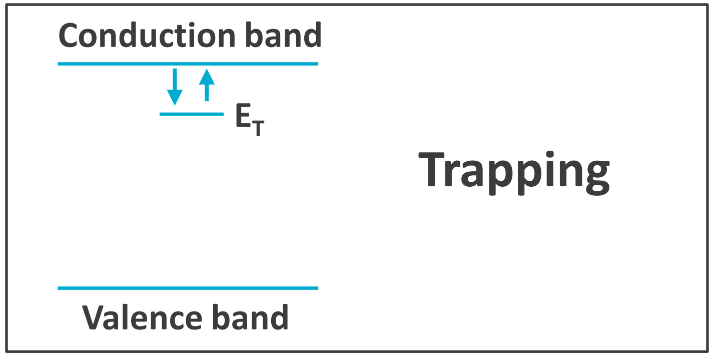
- Fresh vertical GaN diodes show FOM close to GaN limit line
- Degradation in $R_{on,sp}$ and V_{BD} following irradiation results in lower unipolar FOM
- Performance following irradiation is still below Si limit line!

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

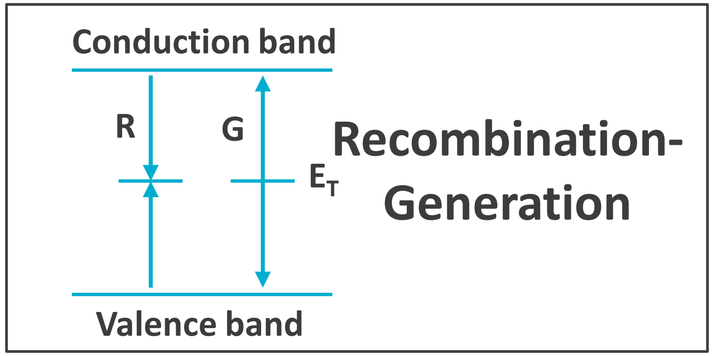
Displacement Damage Introduces States into the Bandgap



Compensation



Trapping



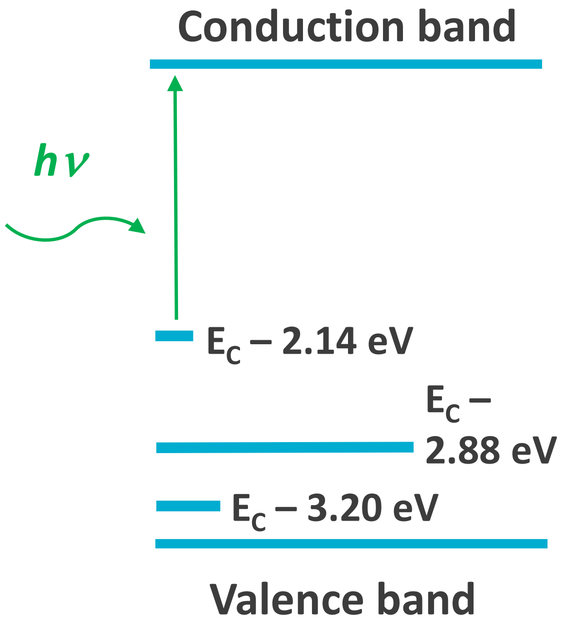
Recombination-Generation

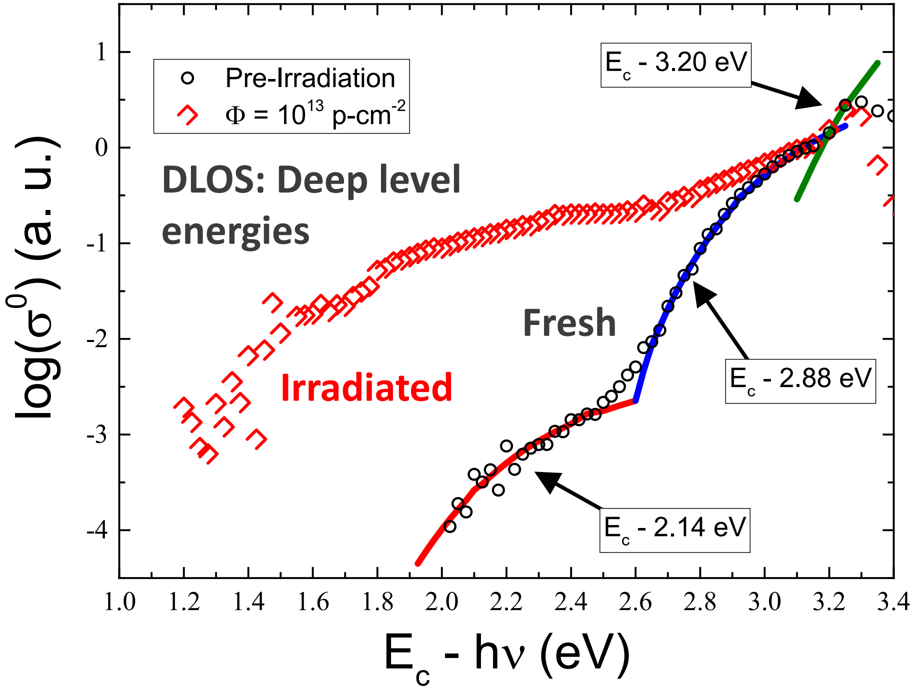
- Energy levels (often referred to as “traps”) are introduced into the semiconductor bandgap by broken crystal symmetry

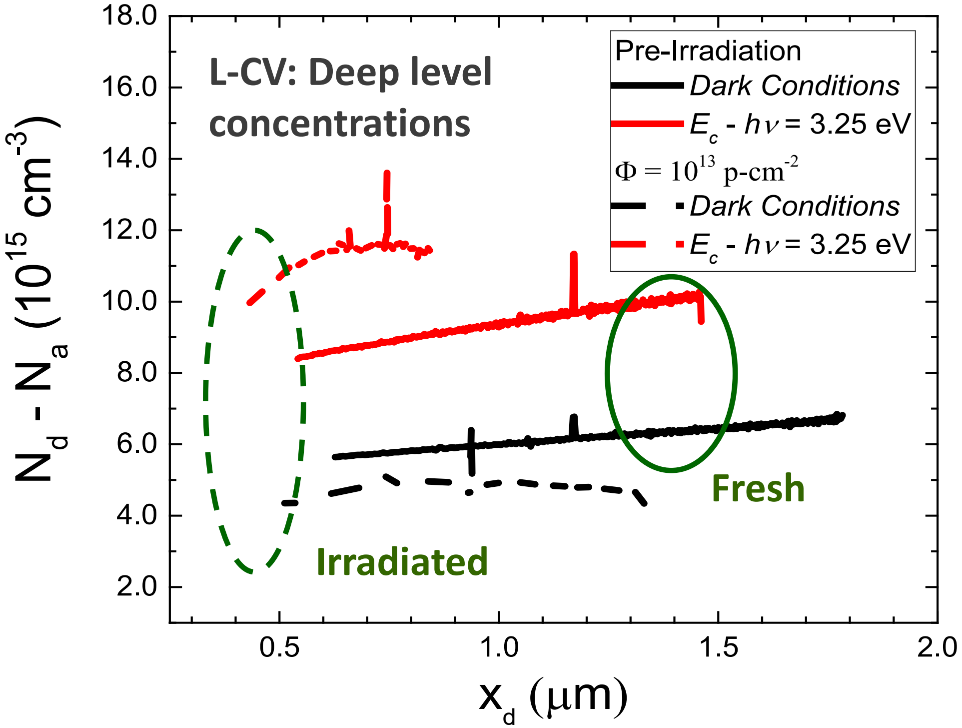
- These traps can cause a number of changes to device performance
  - Change in doping due to compensation, hence change in breakdown voltage
  - Trapping of carriers and associated time-dependent effects
  - Carrier recombination and generation via deep levels affects forward and reverse bias currents
  - Change in carrier lifetime may impact switching speed
  - Currents due to trap-assisted tunneling and/or hopping conduction

- *Radiation-induced changes at the atomic scale may have significant system-level impact!*

Investigation of Changes to Deep Levels due to Irradiation





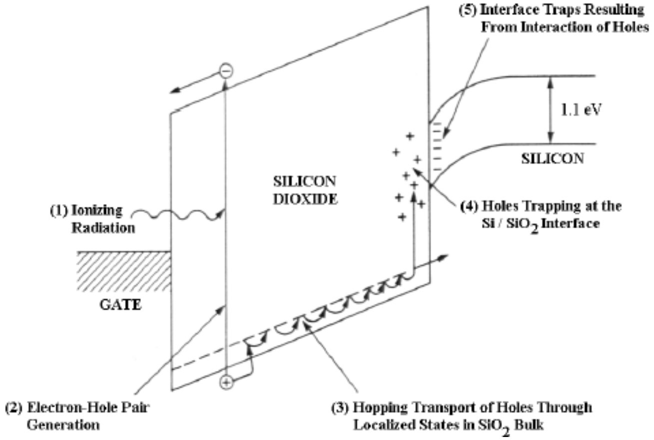


- DLOS = Deep-Level Optical Spectroscopy
  - Determines deep-level energies (and broadening)
- L-CV = Lighted capacitance-voltage
  - Determines deep-level concentrations

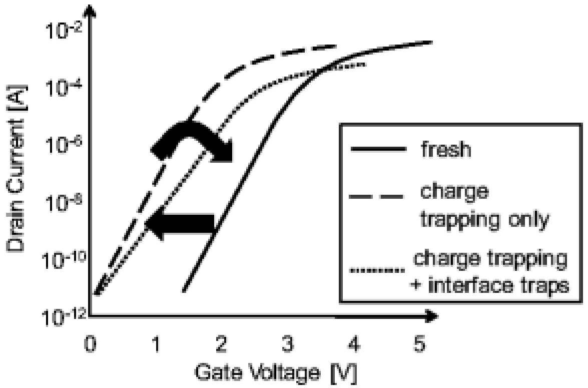
- DLOS indicates increased absorption and broadening after irradiation
- L-CV indicates increased deep-level concentration after irradiation

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

Ionizing Radiation May Likewise Impact Device and System Performance



C. Claeys and E. Simoen, “Radiation Effects in Advanced Semiconductor Materials and Devices,” Springer-Verlag (2002)

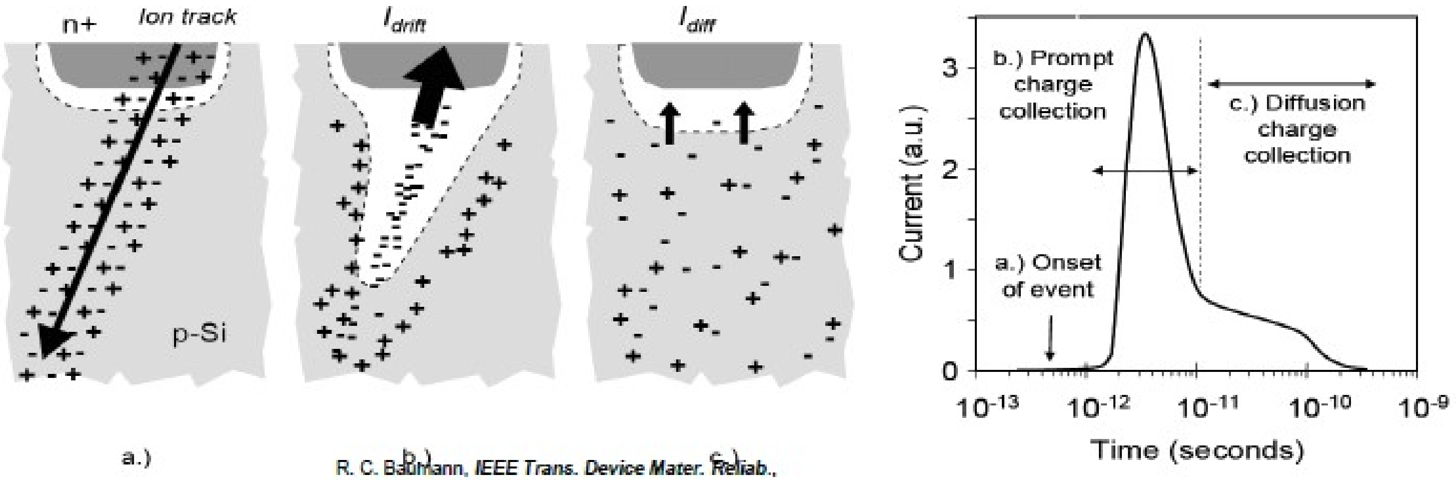


M. Bagetin et al., “Radiation Effects on NAND Flash Memories,” Springer-Verlag (2010)

- Ionizing radiation generates electron-hole pairs in the device
    - Subsequent transport due to drift and diffusion
    - May become trapped in bulk and/or interfacial defects
- Trapped charge changes device characteristics
    - For MOS devices, shift in threshold voltage and/or sub-threshold slope affects gate drive and on/off characteristics
    - Charge trapped in deep states (long time constants) result in DC shifts in device performance (reliability concern)
    - Charge trapped in shallow states (short time constants) results in transient shifts in device performance
    - Charge trapping in passivation dielectrics may impact edge termination and breakdown in high voltage devices
- *Again, radiation-induced changes at the atomic scale may have significant system-level impact!*

Single Event Effects (SEE) Can Be Caused by a Single Particle

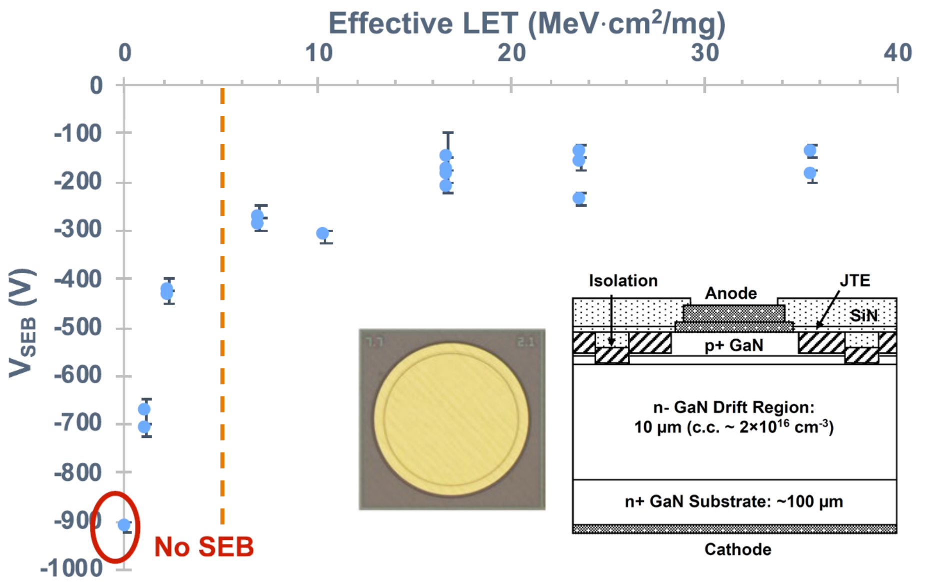
- A single high-energy particle strikes a device
- An *ionized track* of electron-hole pairs is generated
- Generated electrons and holes move by drift and diffusion
- The effect is a function of the device’s bias state and the energy of the ion
  - Single-Event Upset (SEU)
  - Single-Event Latchup (SEL)
  - Single-Event Burnout (SEB)
- Effects can be temporary or destructive



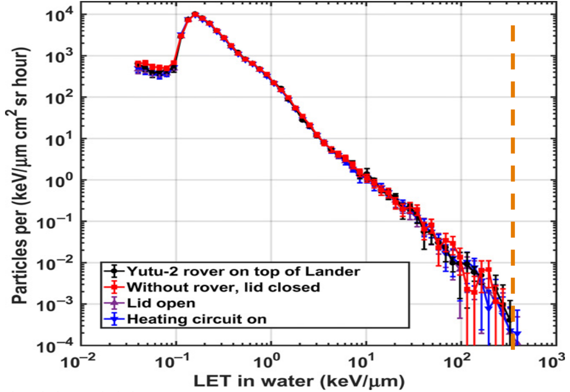
R. C. Baumann, *IEEE Trans. Device Mater. Reliab.*, vol. 5(3), p. 305-316, Sept. 2005

SEB Risk Requires Derating of WBG Power Devices

- High Voltage Vertical GaN PN diodes (V_{br} ~ 1200V) with 1 mm^2 die area were tested for SEB
- "To get a first estimate of these diodes' vulnerability to SEB from heavy ion irradiation, 22 diodes were taken to the K500 cyclotron at Texas A&M University (TAMU)."
- Devices require derating based on particle Z number and LET, i.e. V_{br} reduced by ~80% for LET >10 MeV·cm^2/mg and/or Z > 18
- However, testing was done at high fluence levels, which contributed to late failures, possibly caused by displacement damage induced leakage currents
- All devices failed as a permanent short circuit
- Additional testing needed at realistic flux/fluence levels and more test articles; additional work underway to harden diodes to SEB and increase V_{br}
- Use of WBG power devices in lunar surface power electronics requires a consideration of voltage bias (i.e. derating); flux, LET, and Z of particles; and circuit susceptibility to device failure



Measured particle flux on Moon



Particle flux increases dramatically during a solar storm

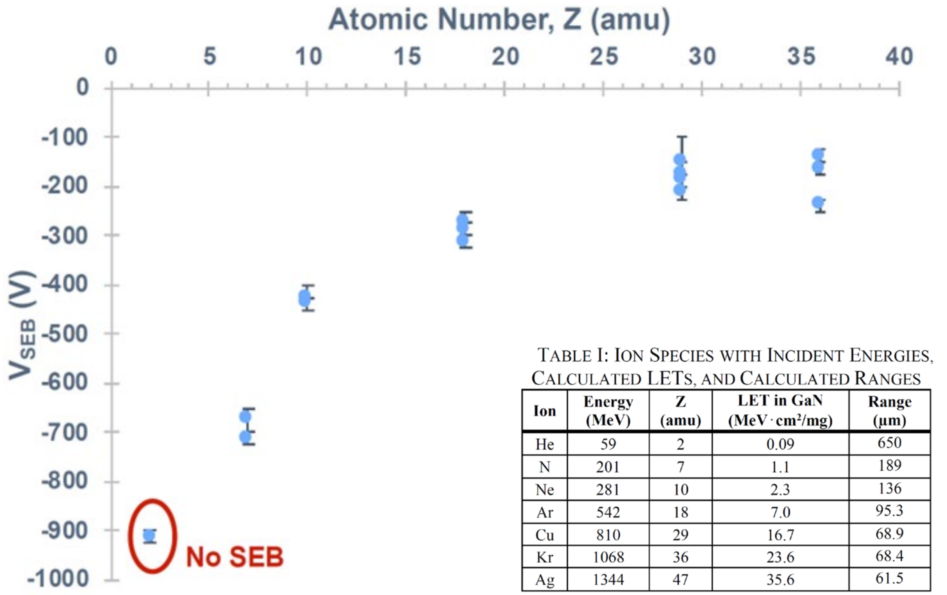


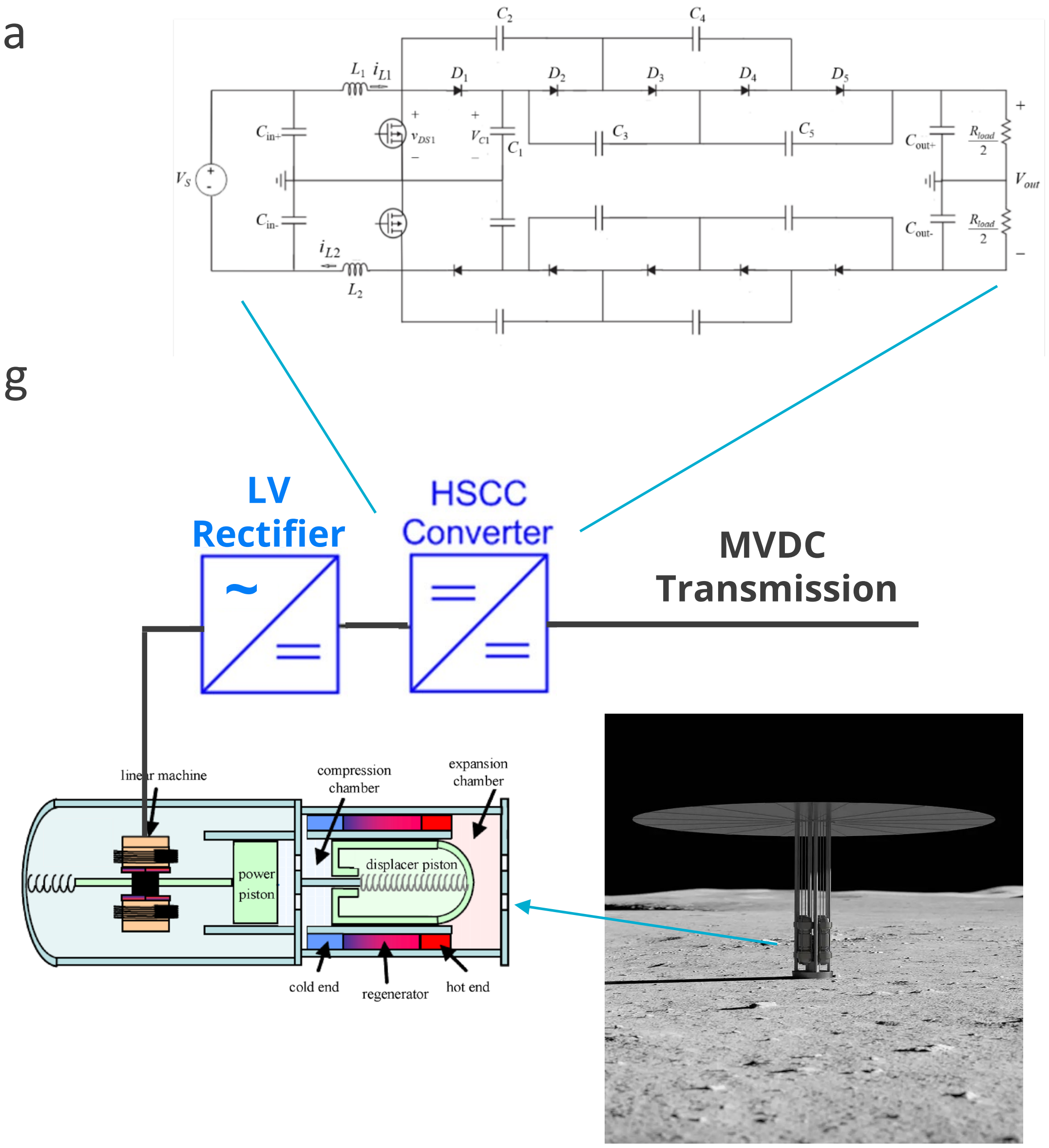
TABLE I: ION SPECIES WITH INCIDENT ENERGIES, CALCULATED LETS, AND CALCULATED RANGES

Ion	Energy (MeV)	Z (amu)	LET in GaN (MeV·cm²/mg)	Range (µm)
He	59	2	0.09	650
N	201	7	1.1	189
Ne	281	10	2.3	136
Ar	542	18	7.0	95.3
Cu	810	29	16.7	68.9
Kr	1068	36	23.6	68.4
Ag	1344	47	35.6	61.5

M. John Martinez et al.; "Single Event Burnout in Vertical GaN Diodes"; SAND2021-2122C; 2021
https://www.science.org/doi/10.1126/sciadv.aaz1334

Summary

- A Hybrid Switched Capacitor Converter may be utilized as a compact solution to boost Stirling Converter voltages to MVDC for transmission
- This enables fission reactors to be located a distance from inhabitants on the Moon
- Building the HSCC with WBG components is key to realizing the circuit with high power density and is expected to improve the resiliency in radiation environments
- Different types of radiation damage may occur
  - Displacement damage
  - Ionization
  - Single event effects
- WBG (especially GaN) devices have been shown to be resilient to neutron, proton, and TID radiation
- Additional work needed to better understand limits associated with SEE



Backup

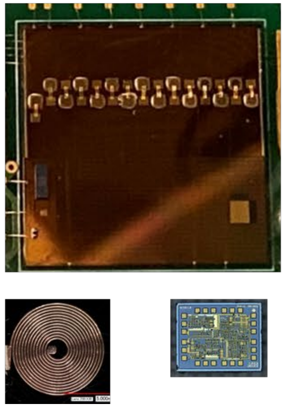

phys.org
brickshelf.com
custombricks.net
www.custombricks.net

FY23 Ending Project Summary (UUR-level)

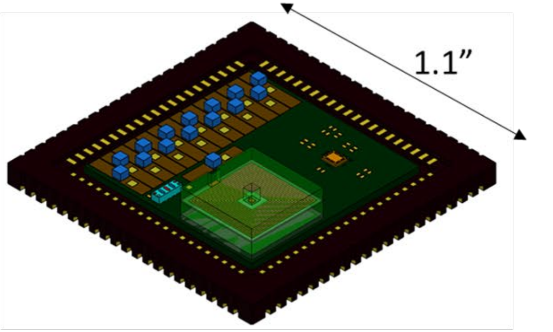
- Numerous high-consequence systems and national security applications have advanced high-voltage components, which rely on bulky and heavy power converters. This project develops a solution that reduces high-voltage power conversion to a single packaged component: a high-voltage chip-scale power converter
- This effort exploits Sandia’s microelectronics development capabilities to realize a compact converter with high boost gain, reasonable conversion efficiency, good voltage stability, and resilience in extreme environments. The team has already fabricated several custom elements and are assembling the first prototypes

PCB scale HV converter

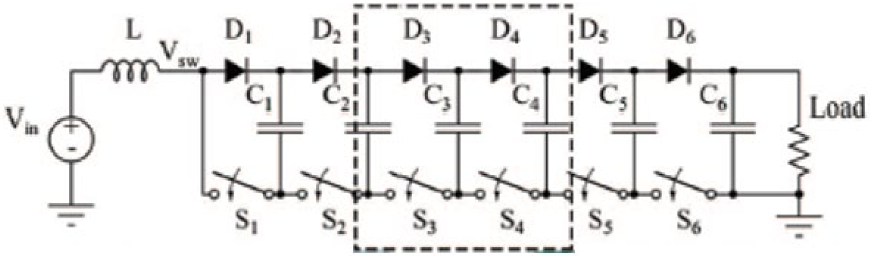
Interposer and Miniaturized power + control elements



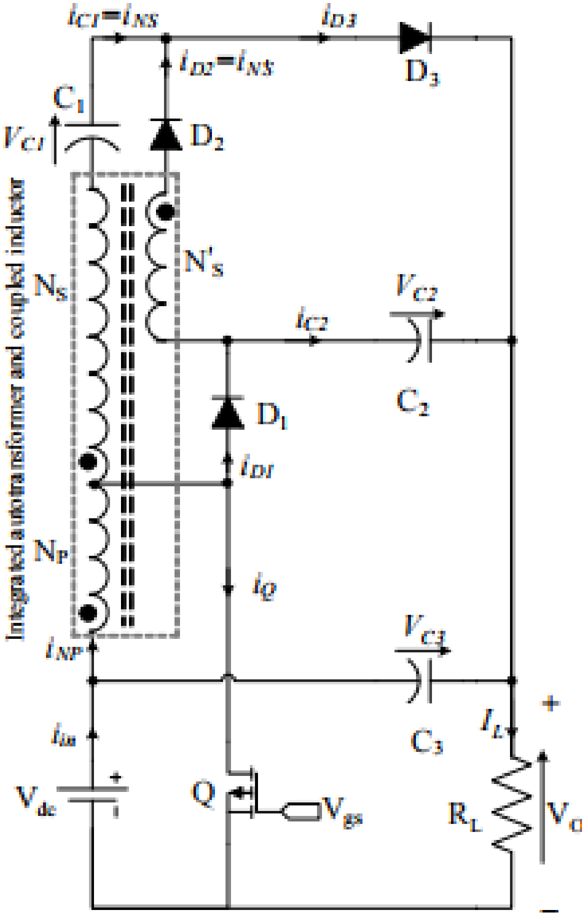
Chip scale HV converter



Let's Consider Prior Approaches to Achieve Higher Gain



Six-stage voltage multiplier with 6 active switches [1]



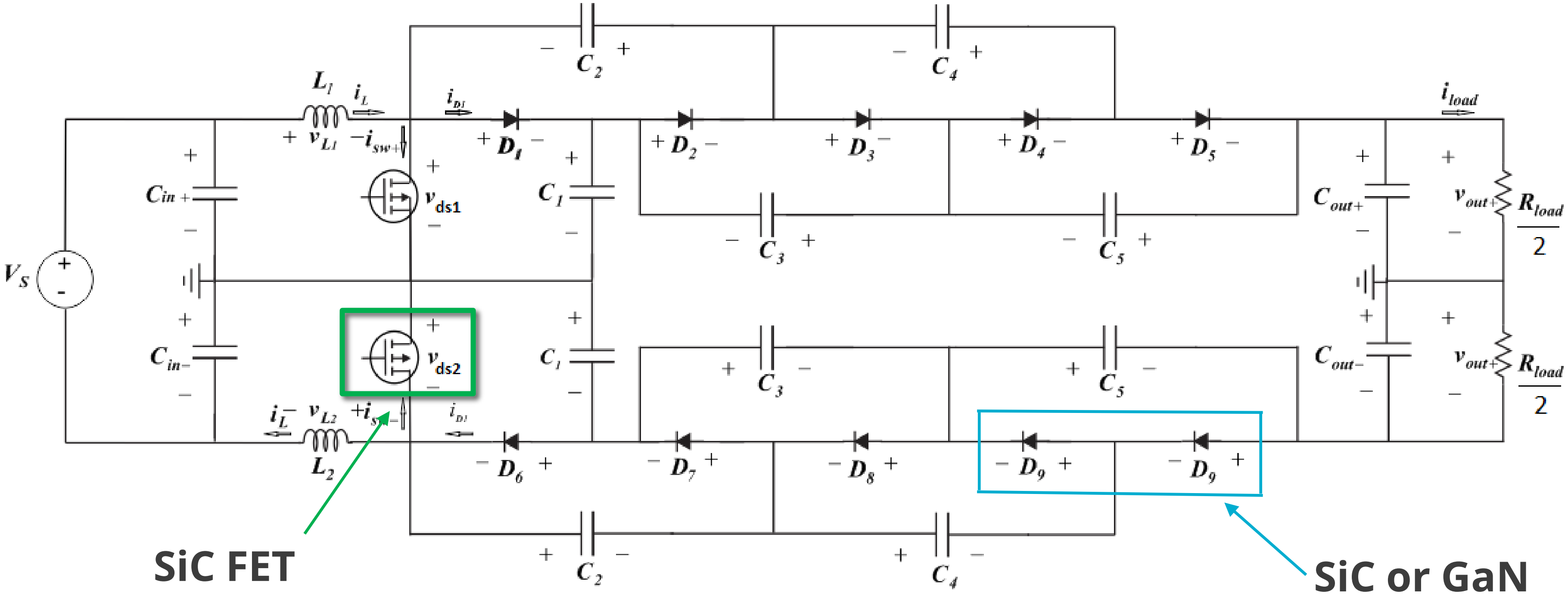
- Various capacitor-diode voltage multiplier circuits have been built demonstrating high gain
- Converters were limited to several hundred volts or low switching frequency

Voltage multiplier with autotransformer and coupled inductor[2]

[1] W. Chen, A. Q. Huang, C. Li, G. Wang and W. Gu, "Analysis and Comparison of Medium Voltage High Power DC/DC Converters for Offshore Wind Energy Systems," in *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 2014-2023, April 2013.

[2] Y. P. Siwakoti, F. Blaabjerg and P. C. Loh, "Ultra-step-up DC-DC converter with integrated autotransformer and coupled inductor," *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, 2016, pp. 1872-1877.

SiC and GaN devices can Further Improve Power Density



SiC FET

SiC or GaN

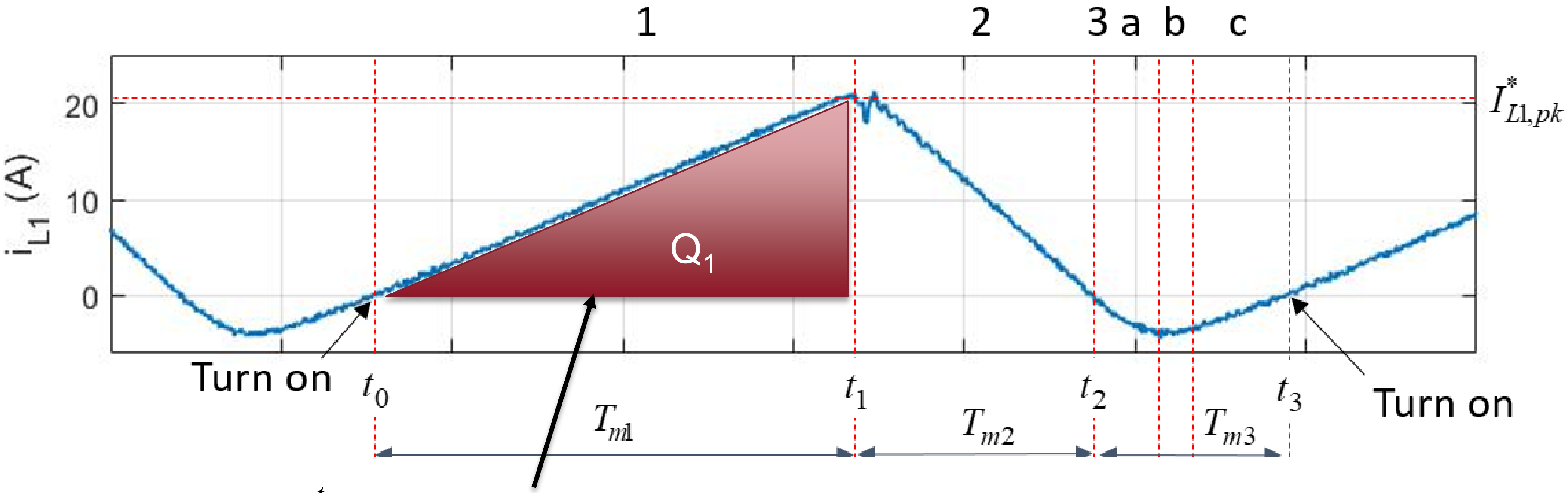
- SiC FET with SiC or GaN diodes simplify circuit design
- Bipolar design halves voltage stress per component for a given output voltage
- Current is shared between multiple paths, reducing parallel component count

A Method to Regulate Input Power while Reducing Switching Loss was Developed

- The input power is computed by summing the charge delivered to the circuit over the three modes

$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

- The charge transferred during Mode 1 is given as the integral of inductor current over the interval



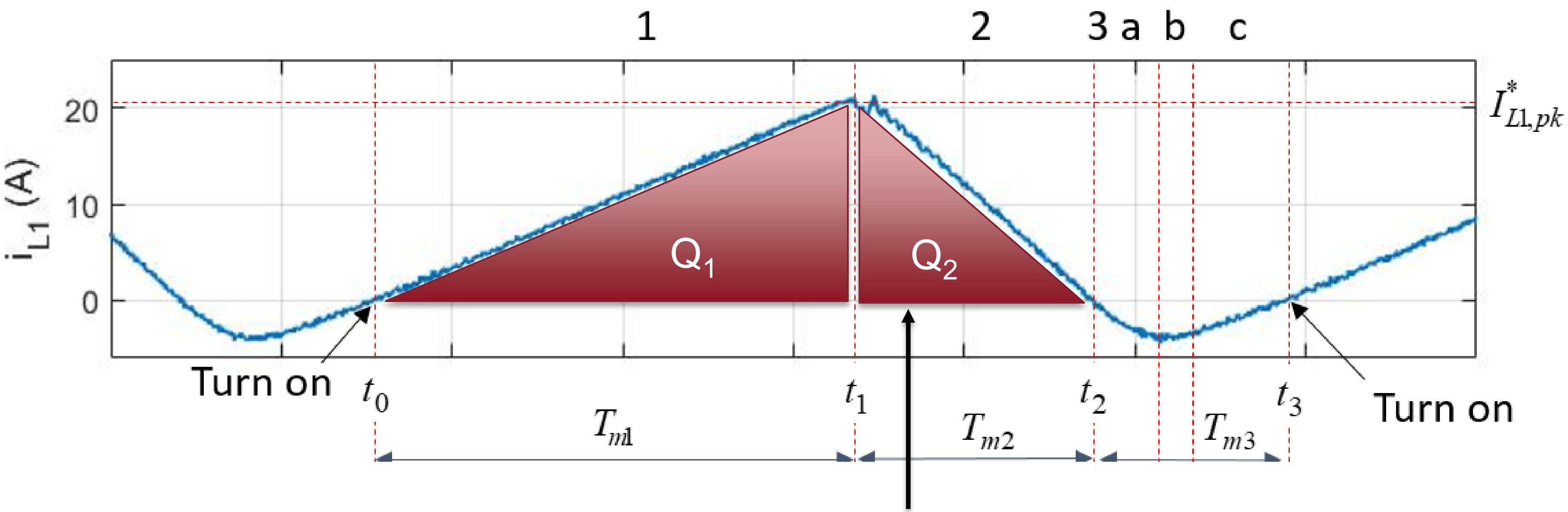
$$Q_1 = \int_{t_0}^{t_1} i_{L1}(t)dt = \frac{I_{L,pk} T_{m1}}{2} = \frac{L}{V_S} I^2_{L,pk}$$

A Method to Regulate Input Power while Reducing Switching Loss was Developed

- The input power is computed by summing the charge delivered to the circuit over the three modes

$$P_{in} = V_S I_{L1} = V_S \frac{\left(Q_1 + Q_2 + Q_3\right)}{T_{sw}}$$

- The charge transferred during Mode 2 is similarly computed



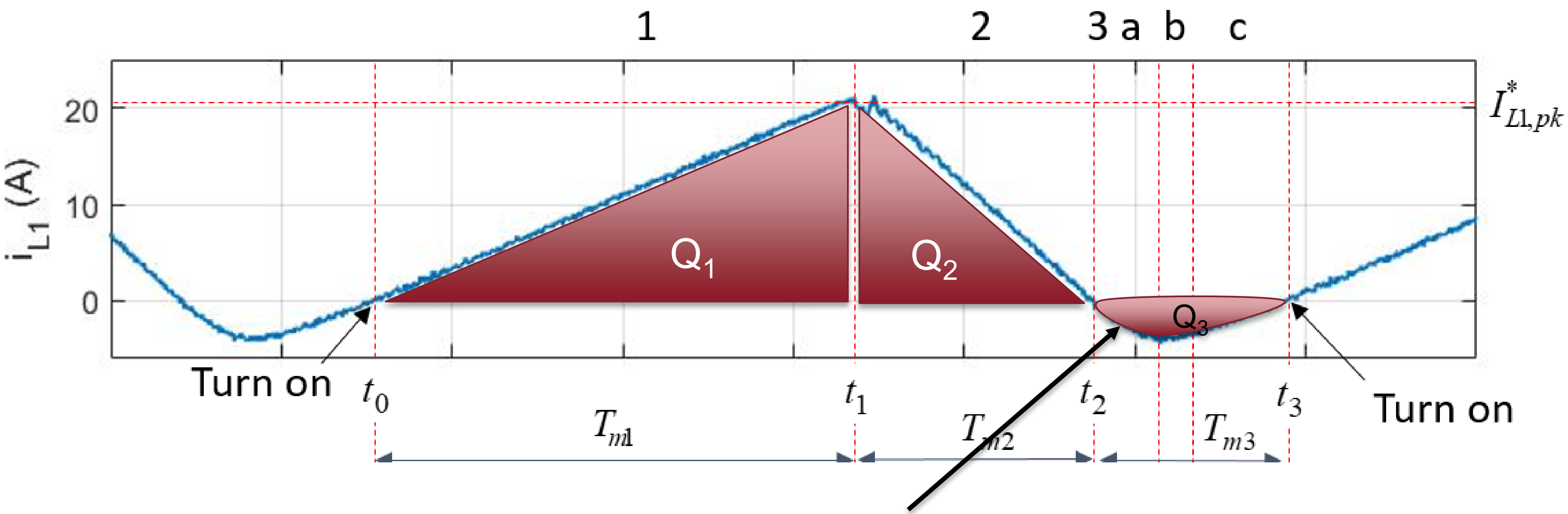
$$Q_2 = \int_{t_1}^{t_2} i_{L1}(t)dt = \frac{I_{L,pk}T_{m2}}{2} = \frac{L\left(N+1\right)}{V_{out} - V_S\left(N+1\right)} I_{L,pk}^2$$

A Method to Regulate Input Power while Reducing Switching Loss was Developed

- The input power is computed by summing the charge delivered to the circuit over the three modes

$$P_{in} = V_S I_{L1} = V_S \frac{(Q_1 + Q_2 + Q_3)}{T_{sw}}$$

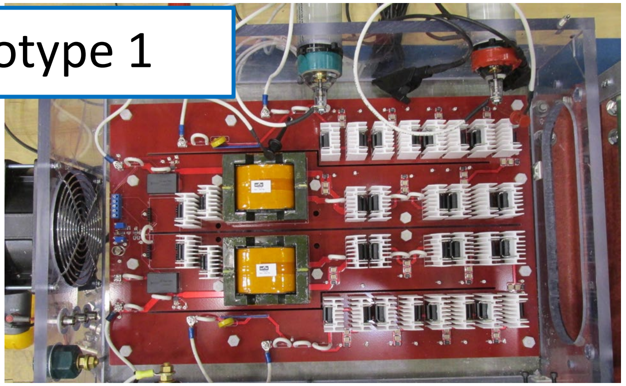
- The charge transferred during Mode 3 is a little more complicated, and is negative



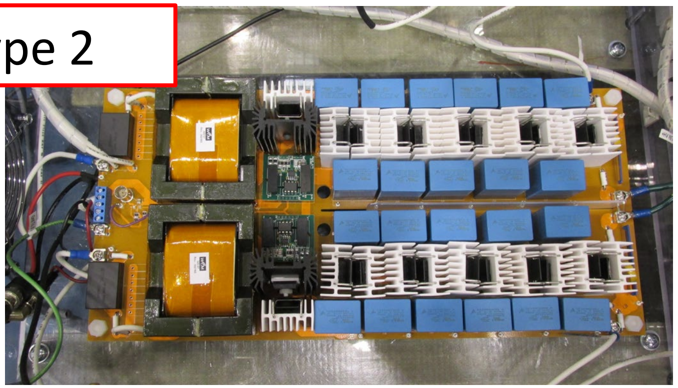
$$Q_3 = \int_{t_2}^{t_2+T_{m3a}+T_{m3b}} i_{L1}(t)dt + \int_{t_3-T_{m3c}}^{t_3} i_{L1}(t)dt = \frac{\tau_{CP}{}^2}{L}\left(0.6301\frac{V_{out}}{(N+1)} - 0.4727\frac{V_{out}{}^2}{V_S(N+1)^2}\right)$$

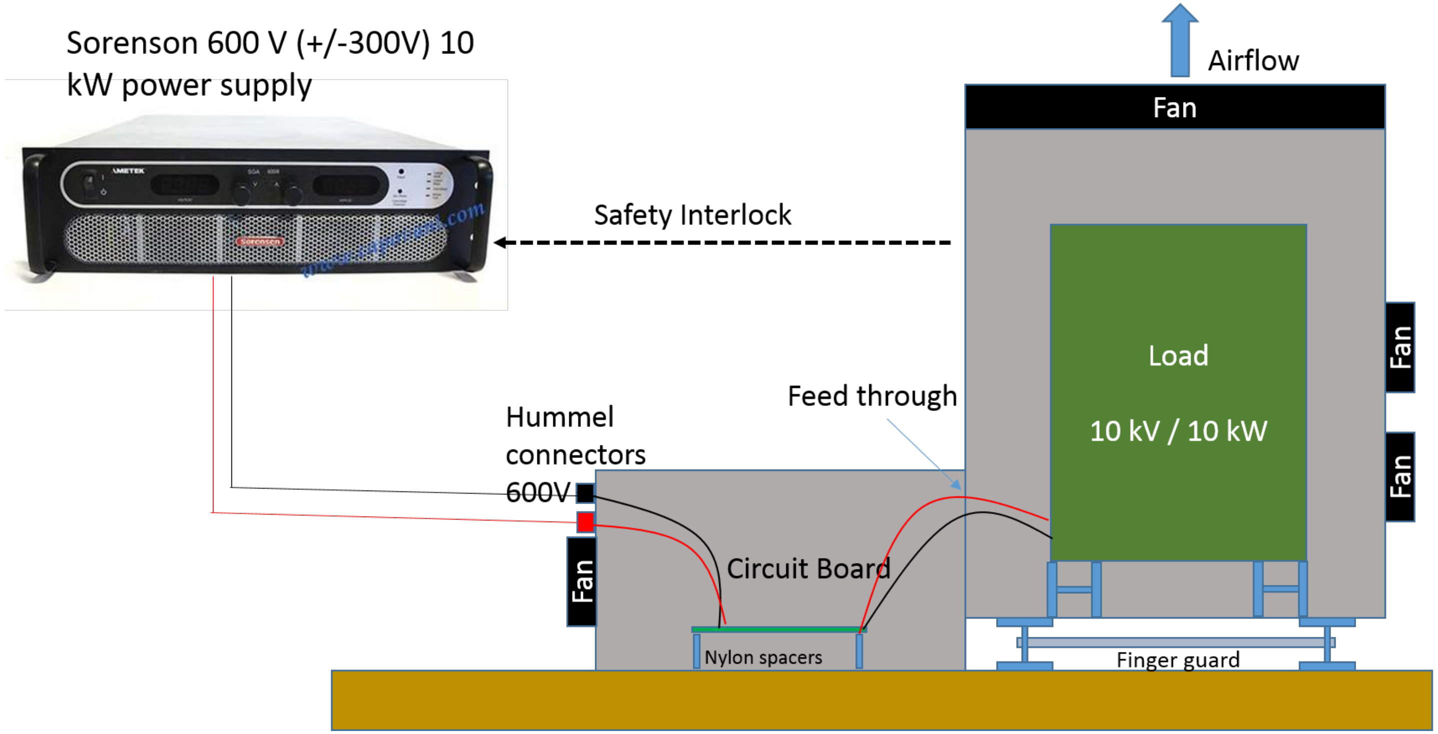
Prototypes 1 and 2 were Compared

Prototype 1



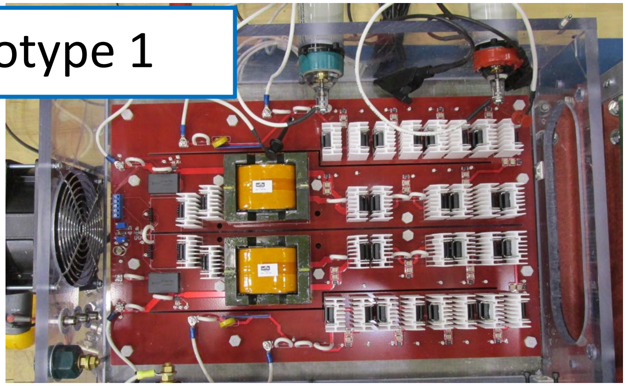
Prototype 2



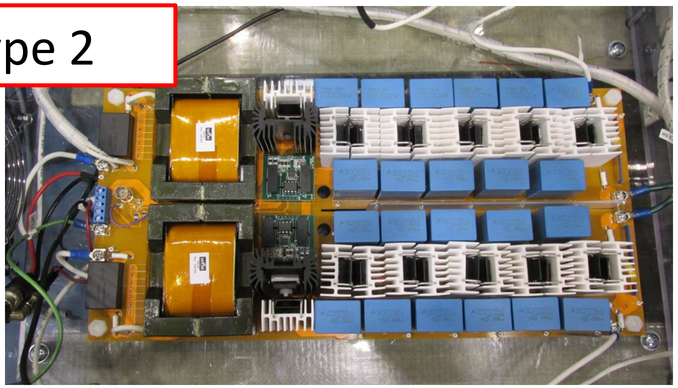


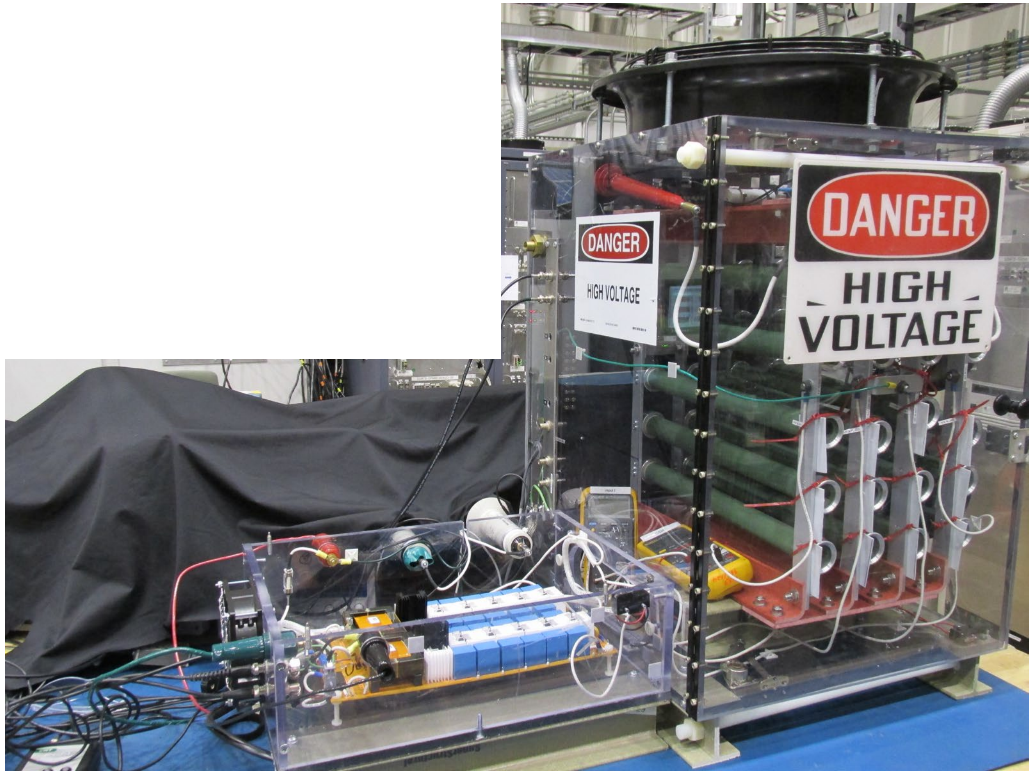
Prototypes 1 and 2 were Compared

Prototype 1



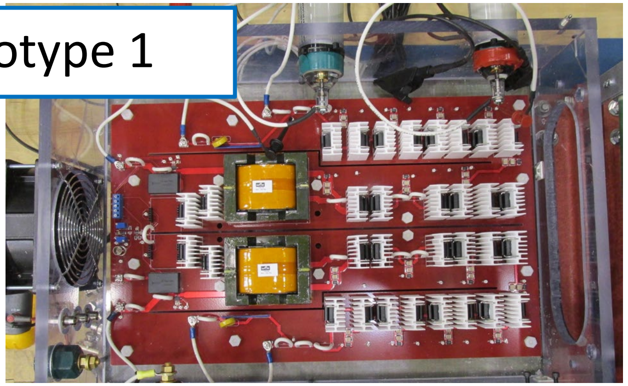
Prototype 2



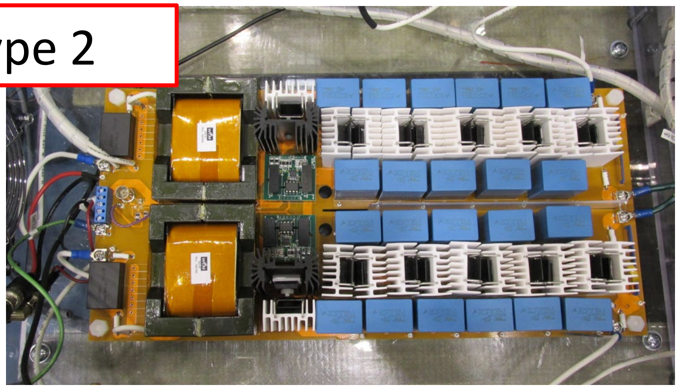


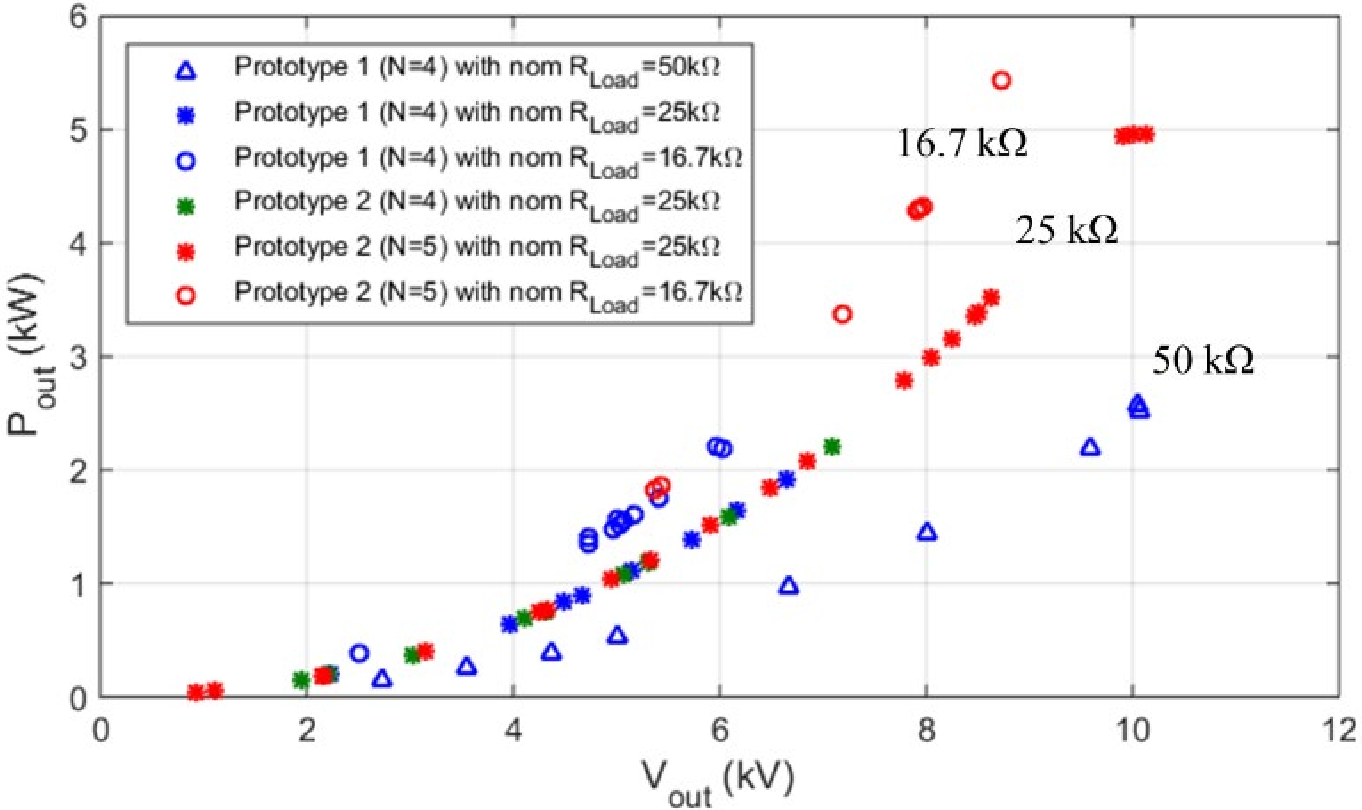
Prototypes 1 and 2 were Compared

Prototype 1



Prototype 2





Ionizing Radiation Creates Charge Carriers

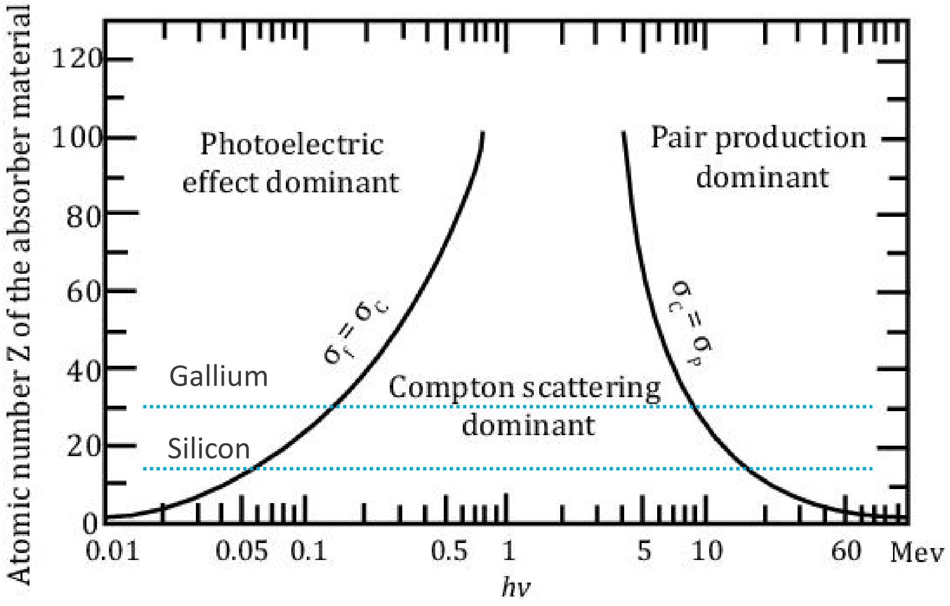
- Second main damage mode
- Typically caused by photons
  - The photon is an electromagnetic “packet” whose is proportional to frequency, inversely proportional to wavelength, and is usually specified in electron volts (eV):

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

- Different interactions take place depending on photon energy and absorbing material atomic number
  - Photoelectric effect
  - Compton Scattering

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

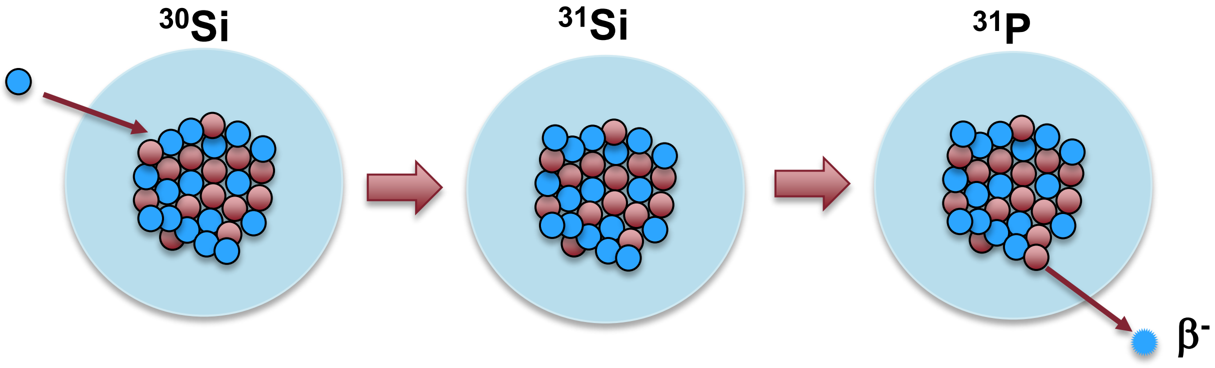
  - Electron-positron pair production
- Persistent damage measure by deposited energy (rad(mat)), transient damage measured by dose rate (rad(mat)/s)

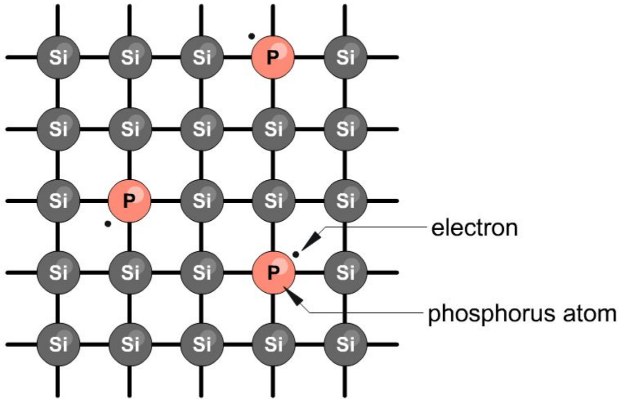


C. Claeys and E. Simoen, “Radiation Effects in Advanced Semiconductor Materials and Devices,” Springer-Verlag (2002)

Transmutation Changes the Chemical Composition and May Dope the Semiconductor

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

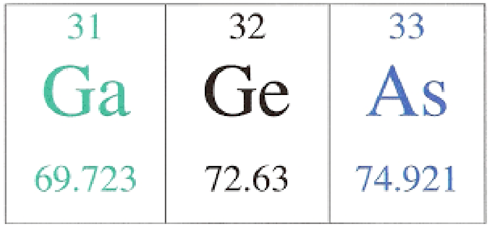




- Other material transmutations

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

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



31	32	33
Ga	Ge	As
69.723	72.63	74.921