



# Radiation Effects Center of Excellence

Annual Review

October 23-25, 2024

Vanderbilt University, Ohio State University, University of California—Santa Barbara,  
University of Texas—Dallas

US Air Force



## Radiation Effects Center of Excellence

Ron Schrimpf  
Principal Investigator

### University Participants

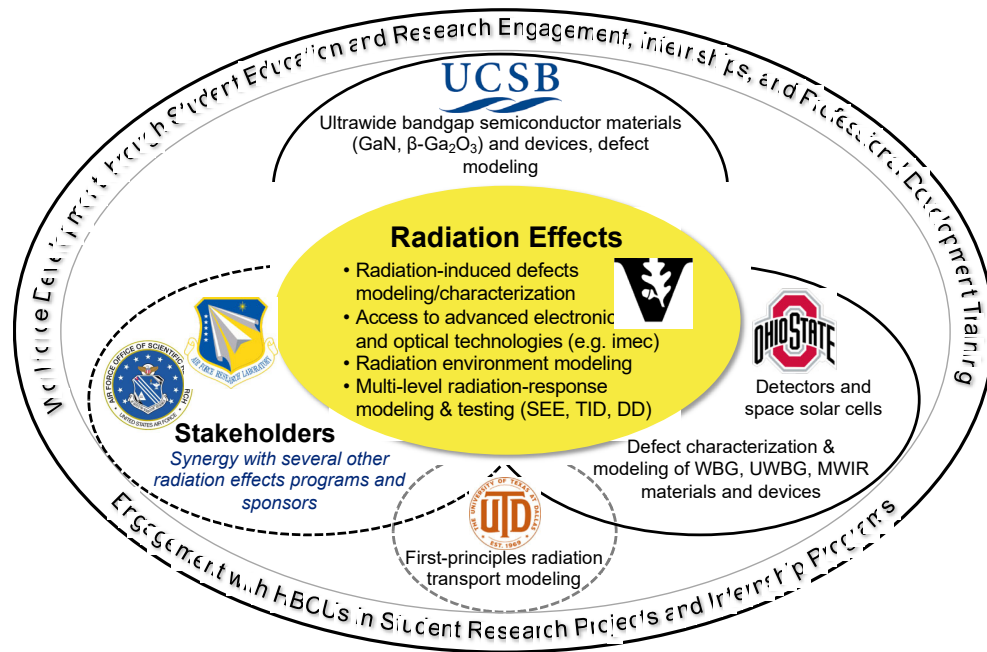
- Vanderbilt
- Ohio State
- UCSB
- UT Dallas
- Fisk
- Tennessee

### Air Force Participants

- AFOSR
- Wright-Patterson
- Kirtland

### AF Program Managers

- Ken Goretta
- Art Edwards
- Michael Yakes



- Develop and apply new predictive capabilities to enable radiation-tolerant designs utilizing emerging materials and technologies
- Use coordinated, state-of-the-art experimental and theoretical methods to determine fundamental radiation-effects mechanisms
- Educate students, scientists and engineers in the radiation-effects discipline
- Interact with AFRL researchers to transfer the resulting technology and train AFRL staff on issues related to radiation effects in electronics



# 2024 Accomplishments



- More than 25 journal articles
- Presentations at multiple conferences (NSREC, RADECS, etc.)
- Best Paper Award at the IEEE Space Computing Conference
- Graduate student interns and degree completions
- Collaborations
  - Among COE universities
  - With MURI universities
  - With AFRL researchers
  - With external organizations (e.g., imec)



# University Team Members



- Vanderbilt
  - Ron Schrimpf, Mike Alles, Dan Fleetwood, Robert Reed, Sokrates Pantelides, Enxia Zhang (transitioned to UCF), Mona Ebrish
- Ohio State
  - Steve Ringel, Aaron Arehart, Siddharth Rajan
- UCSB
  - Jim Speck, Esmat Farzana (transitioned to Iowa State), Chris Van de Walle
- UT-D
  - Max Fischetti
- Fisk University
  - Arnold Burger
- Tennessee
  - Maik Lang
- The team has a long history of successful collaboration.
  - Multiple MURIs
  - Many joint publications



# Concentration Areas



- Experimental/theoretical defect identification and mechanisms for defect creation, evolution, and transformation in new materials systems
  - Emphasis on WBG materials, particularly GaN
- Multiscale predictive modeling
- Single-event effect experiments, testing, and modeling with validation and verification
- Development of modeling tools at the material, device, circuit, and integrated-circuit levels that incorporate the physical mechanisms that determine SEE in nanoscale Si technologies
- Algorithm and circuit & system architecture dependence of radiation sensitivity
- Workforce development (collaboration with SCALE)



# Task organization



Concentration Area	Vanderbilt	OSU	UCSB	UT-D	Key Collaborations and Resources
Experimental & theoretical defect studies	Irradiation, electrical and optical characterization, theory	Material & device characterization, defect spectroscopies	Advanced UWBG materials (e.g., GaN, Ga <sub>2</sub> O <sub>3</sub> )	Monte Carlo transport simulations, theory	AFRL directorates and DoD contractors
Multiscale predictive modeling	Radiation environment & transport; circuit, device, & system sims	Material & device characterization for V&V		High-energy carrier simulations	Other USG-sponsored program interest
Single-event effects experiments & modeling	Radiation testing, including SETs and single-event damage	Provide detector & solar cell devices	Provide UWBG power devices	Examination of carrier thermalization	DURIP-funded test systems, samples from collaborators
Development of modeling tools	Incorporation of radiation-effects models in design flows			Extension of Anduril Monte Carlo code	Commercial companies and tool vendors
Algorithm and circuit & system architecture effects	Development & incorporation of rad-effects models in system tools				AFRL, NASA MBMA and MBSE, SEAM software
Workforce development	Student research, professional development	Student research, professional development	Student research, professional development	Student research, professional development	SCALE program, TLSAMP, SMART program



# Collaborative Activities



- Comparison of single-event effects in wide-bandgap materials
  - Vanderbilt, OSU, UCSB, UT-D
- Single-event effects in GaN devices at high electric fields
  - Vanderbilt, OSU, UCSB, UT-D, UTK
- Radiation effects in  $\text{Ga}_2\text{O}_3$  diodes and MOSFETs
  - Vanderbilt, OSU, UCSB, ISU, AFRL, Sandia
- Defect spectroscopy in wide-bandgap materials
  - OSU, UCSB
- Radiation-induced carrier thermalization and track structure effects
  - Vanderbilt, UT-D
- Fault propagation in radiation-tolerant microprocessors
  - Vanderbilt, AFRL



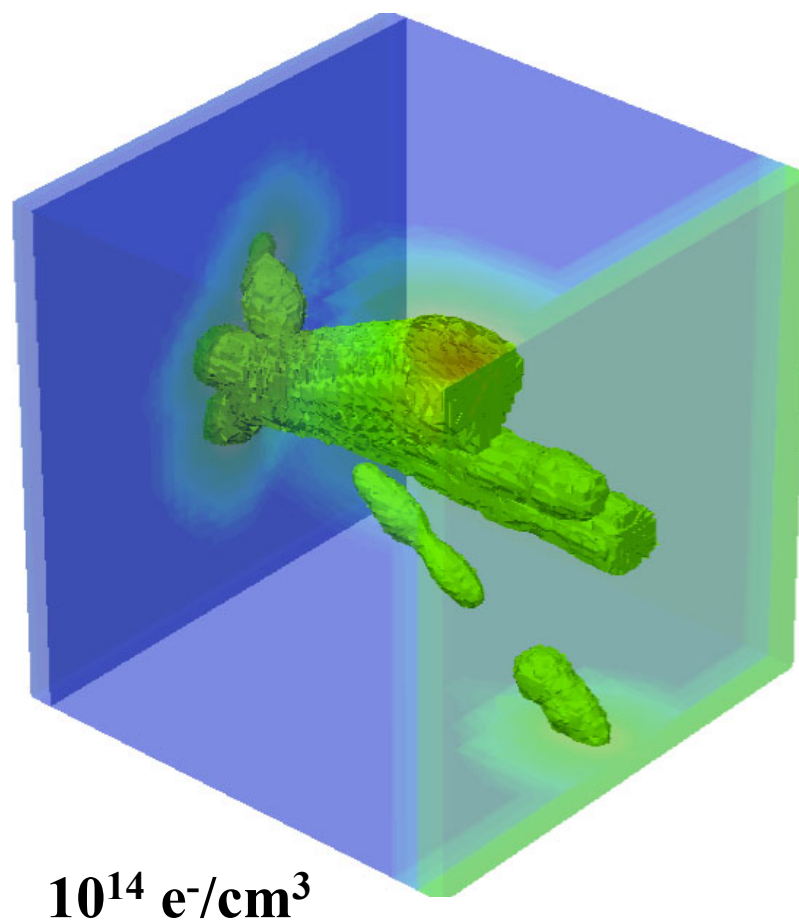
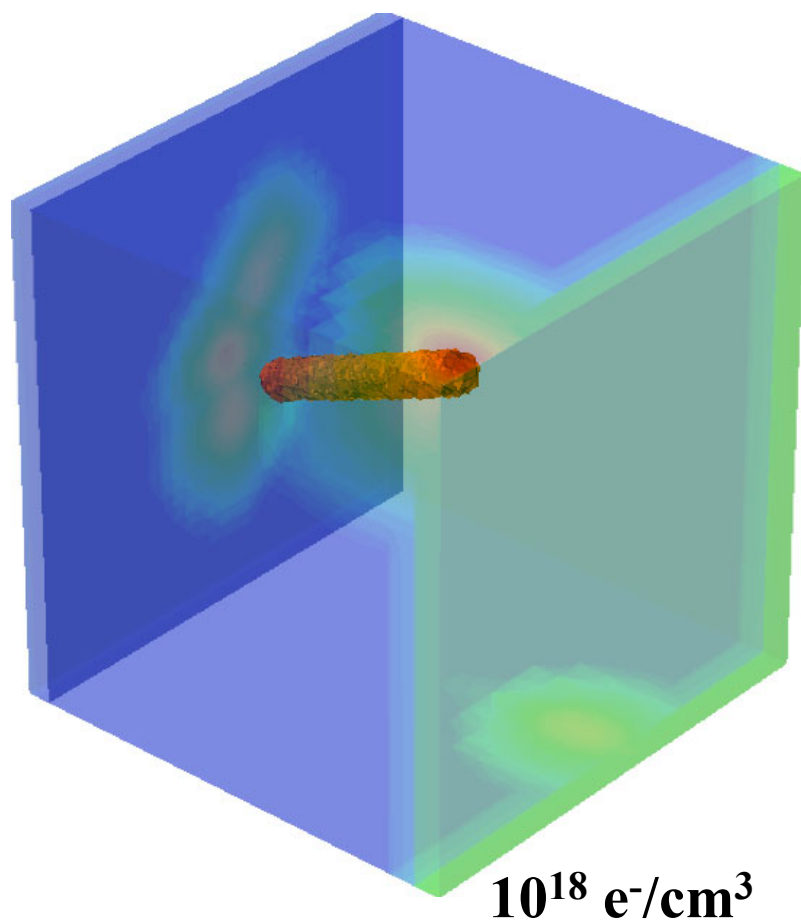
# Highlights — 2023-24



- Radiation-effects session for 2025 MRS Meeting
  - Organized by Mia Jin, Tania Roy, and Dan Fleetwood
- Single-event burnout in GaN diodes with improved termination structures
- Full-band Monte Carlo simulation of radiation-generated charge-track structure
- Radiation response of improved  $\text{Ga}_2\text{O}_3$  diodes
- Molecular dynamics for silicon single-event displacement damage
- Threshold voltage hysteresis and gate leakage in AlGaN/GaN HEMTs
- Role of epitaxial layer thickness in single-event burnout of  $\text{Ga}_2\text{O}_3$  diodes
- Algorithm and configuration dependence of SEE in a radiation-hardened microcontroller

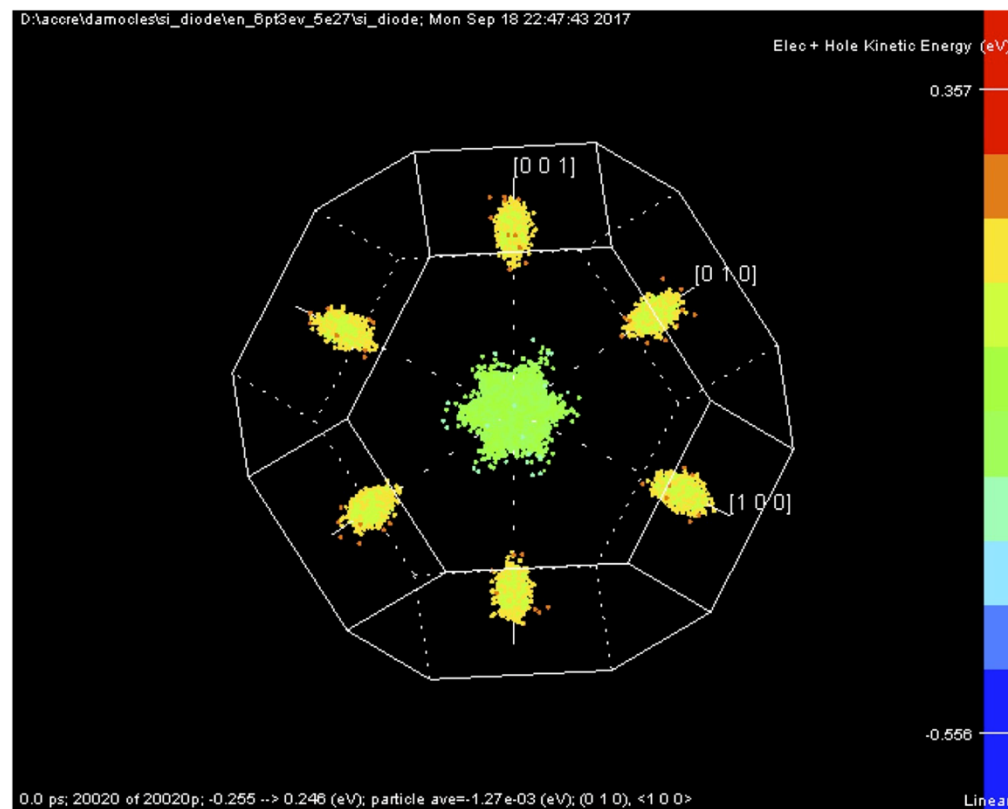


Radiation effects can be temporary,  
cumulative, or catastrophic

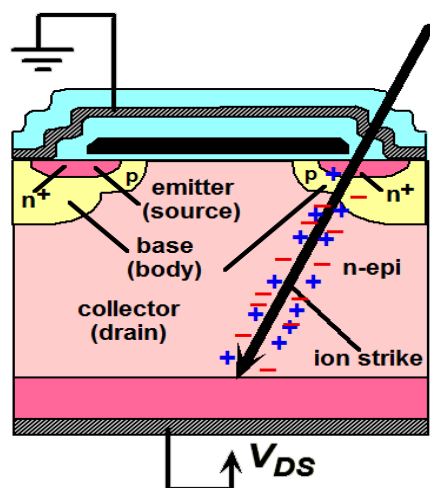


# Radiation effects depend on the bias, ion characteristics, and material properties

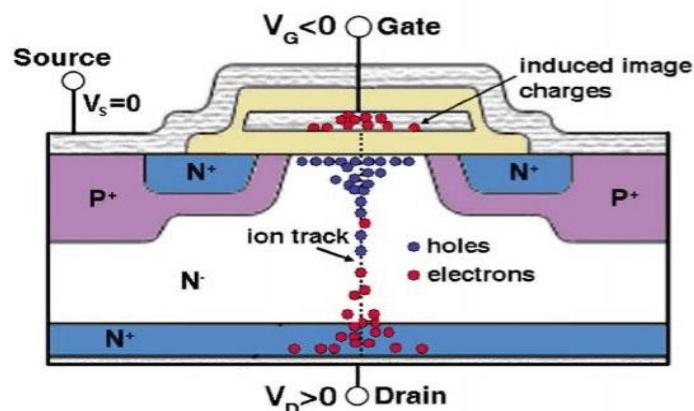
- Evolution of radiation-generated carriers in  $k$ -space
- Energy-loss mechanisms are important
- Predicting event rates depends on determining failure (or upset) criteria



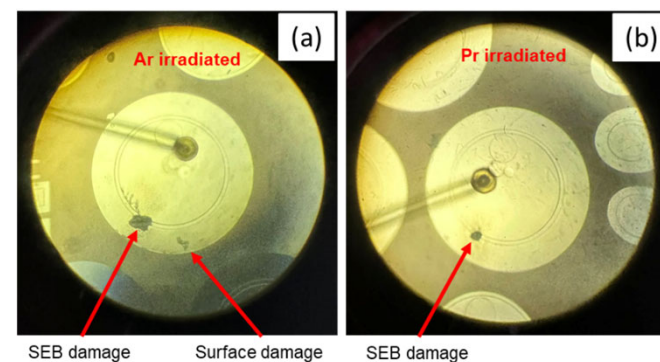
# Single-Event Effects in Power Devices



Single-Event Burnout



Single-Event Gate Rupture



Single-Event Burnout  
of  $\beta\text{-Ga}_2\text{O}_3$  Schottky barrier diodes  
(Islam, et al. 2024)



# Single Event Effects in WBG Materials and Devices



- Caused by
  - Nuclear reactions
  - Ionization
  - Displacement damage
- Interaction induces
  - Localized excess electron hole pairs
  - Localized structural damage
- Effects
  - Single-event burnout
  - Single-event gate rupture
  - Single-event leakage current
  - Defect formation

# Key Questions for the COE

- Why do WBG devices fail at such a low fraction of the rated breakdown voltage in heavy-ion environments?
- What is the relationship between applied voltage and ion LET that results in failure?
- What is the appropriate failure criterion that can be used in predictive modeling? (stored energy, peak field, local power...)
- How do different materials compare? (GaN, SiC, Ga<sub>2</sub>O<sub>3</sub>, Si)
- What is the role of defects?
- Does the bandgap matter, or is it related to something like void formation?
- What is the role of carrier thermalization?

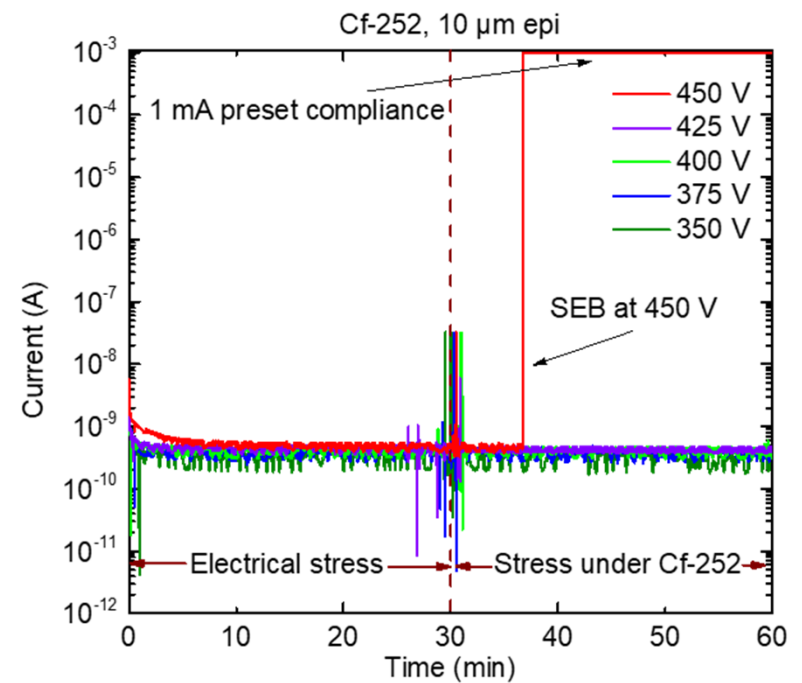
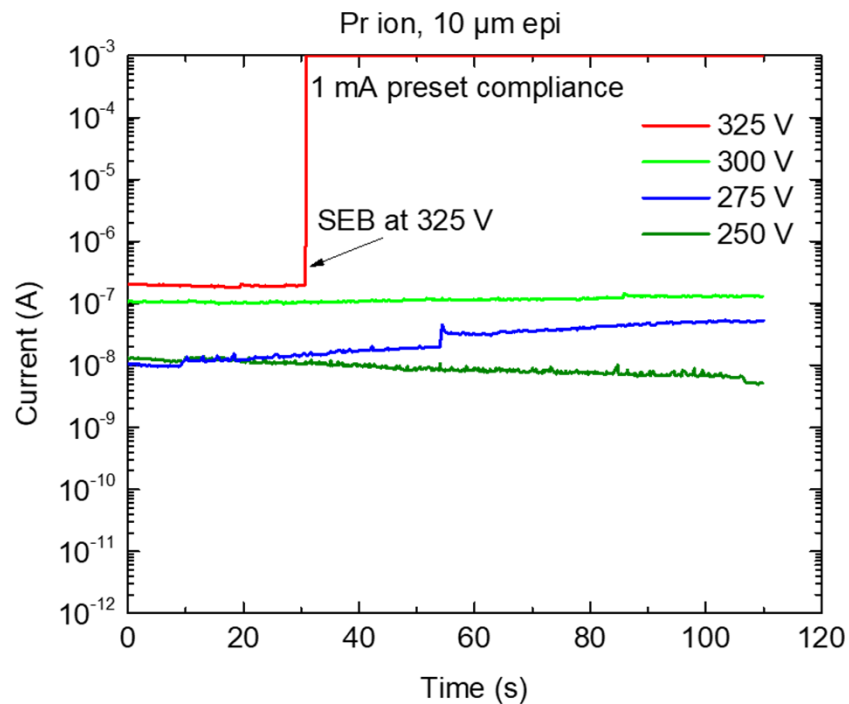
Progress on all of these questions

# Testing approach used for COE experiments

- Compare response to ions with different ranges and LETs
- Accelerator experiments
  - TAMU and VU
- Cf-252 fission fragments
- Am-241 alpha particles
- 10-keV x-ray irradiation

Ion/source	Energy (MeV)	LET in $\beta\text{-Ga}_2\text{O}_3$ (MeV-cm <sup>2</sup> /mg)	Range in $\beta\text{-Ga}_2\text{O}_3$ ( $\mu\text{m}$ )
<sup>40</sup> Ar (TAMU)	15	6.4	101.8
<sup>141</sup> Pr (TAMU)	15	46.5	68.9
O <sup>6+</sup> (Pelletron)	12	5.5	4.3
Cf-252	5.9	10-45	3-10

# SEB Results for $\text{Ga}_2\text{O}_3$ Diodes

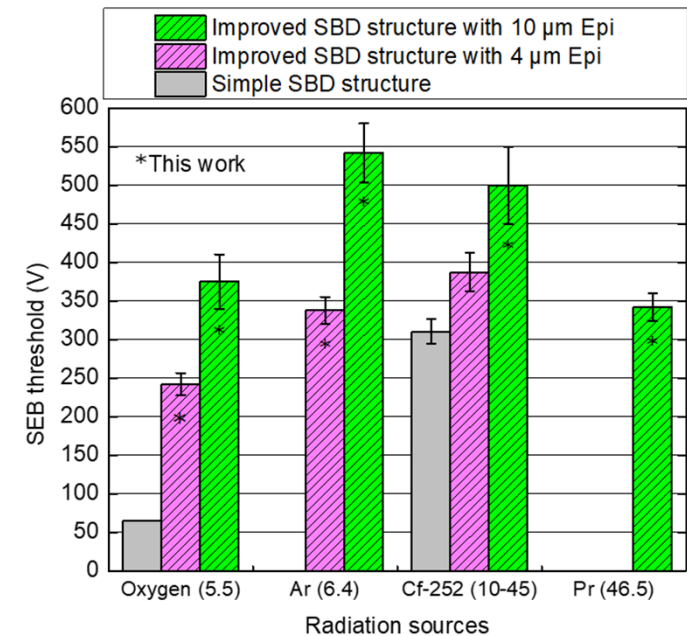


- Collaboration of Vanderbilt, Iowa State, and UCSB

# Analysis of heavy ion induced SEB in $\beta$ -Ga<sub>2</sub>O<sub>3</sub> SBDs

Simple structure: Pt SBCs, no field plates, 10- $\mu$ m epi  
Improved structure: Pt cap/PtOx SBC, FP, dielectric material, 4 or 10  $\mu$ m epi

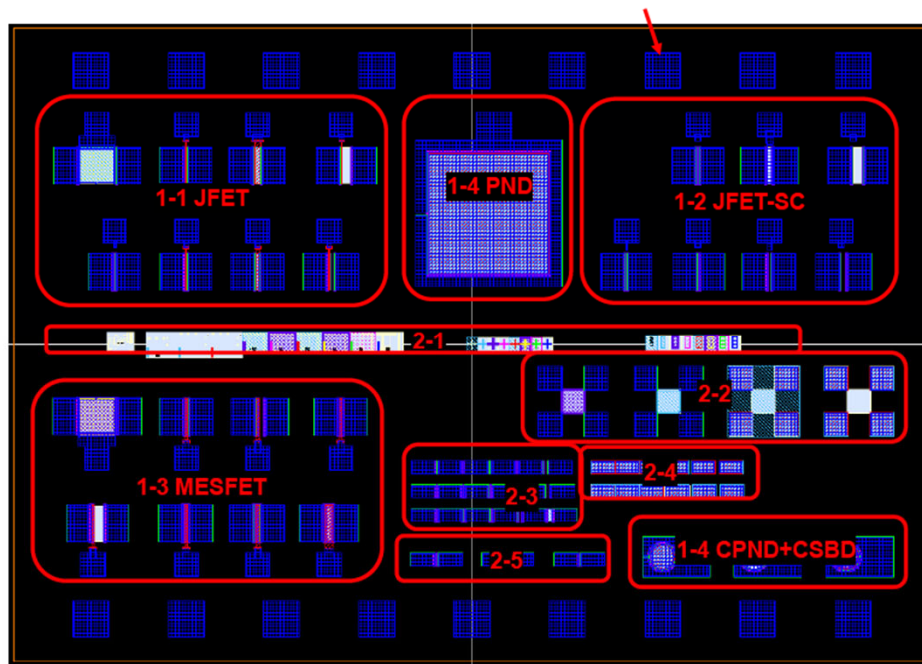
- **~60% SEB tolerance increase** with Cf-252 irradiation in 10  $\mu$ m SBDs (Electrical breakdown limit also increased)
- **Ultra-low SEB threshold with O<sup>+</sup> ions:**
  - high ion-flux of  $5 \times 10^7$  ions/cm<sup>2</sup>/s and fluences up to  $4 \times 10^9$  ions/cm<sup>2</sup>/s
  - At these large fluences, significant amounts of total ionizing dose and displacement damage are delivered to devices, resulting a cumulative damage mechanism.
  - **Charged defect migration** at high electric fields causing lower SEB threshold with O<sup>+</sup> ion.



1. R. M. Cadena *et al.*, "Low-energy ion-induced single-event burnout in gallium oxide Schottky diodes," *IEEE Trans. Nucl. Sci.*, vol. 70, no. 4, pp. 363-369, April 2023.
2. S. Islam *et al.*, "Single-event burnout by Cf-252 irradiation in vertical  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> diodes with Pt and PtOx Schottky contacts and high permittivity dielectric field plate," Dev. Res. Conf. (DRC), Santa Barbara, CA, USA, June 26-29, 2023, pp. 20-21.
3. S. Islam *et al.*, "Single-event burnout in vertical  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> diodes with Pt/PtOx Schottky contacts and high-k field-plate dielectrics," *IEEE Trans. Nucl. Sci.*, vol. 71, no. 4, pp. 515-521, Apr. 2024



# Shared test structures



## 1. Device arrangement

### 1. Main devices

1-1: JFET:  $L_{JTE}=4,10,40,80\mu\text{m}$ ;

$L_{Gate}=2,10,20,50,300\mu\text{m}$

1-2: JFET-SC:  $L_{JTE}=4,10,40,80\mu\text{m}$ ;

$L_{Gate}=2,10,20,50\mu\text{m}$

1-3: MESFET:  $L_{JTE}=4,10,40,80\mu\text{m}$ ;

$L_{Gate}=2,10,20,50,300\mu\text{m}$

1-4: CPND: Ohmic and Schottky PGaN, CSBD, PND[1mm\*1mm PO pad].

$L_{JTE}=10\mu\text{m}$

### 2. Test devices

2-1: Inspection Patterns (Profilometer pad, alignment marker, verniers, resolution bars, lithography inspection pattern, etc.)

2-2: Hall Effect

2-3: N -LTLM

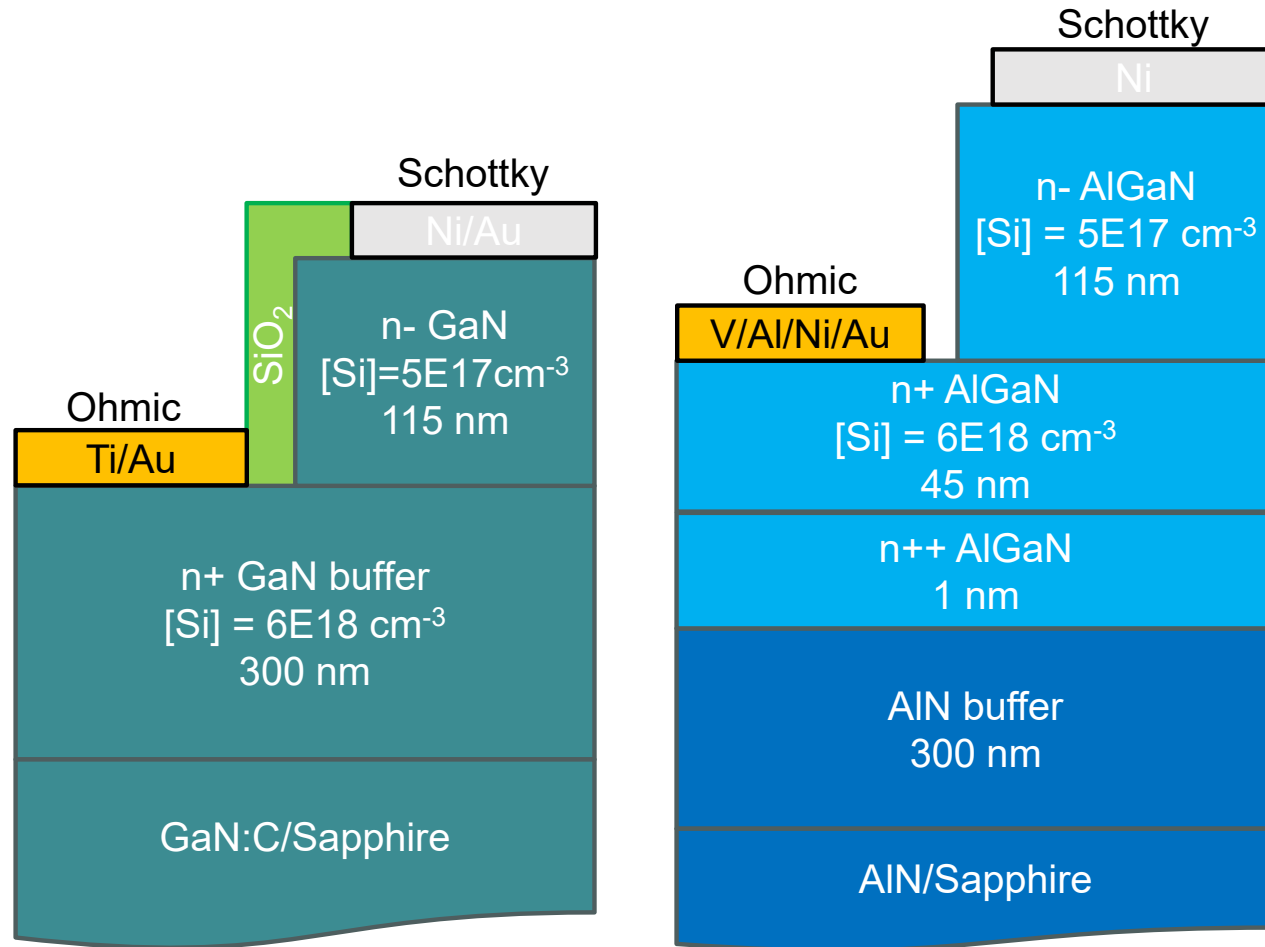
2-4: P -LTLM

2-5: Isolation:  $L_{SHJ} = 20, 10, 5 \mu\text{m}$

- Close coordination with MURI team and AF researchers
- New devices received from PSU in September

# Test structures for comparing GaN and AlGaN

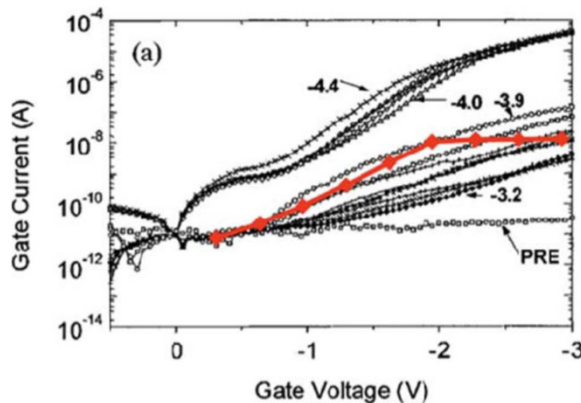
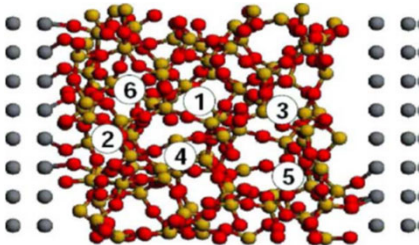
- Fabricated at UCSB
- Thin layers permit high and uniform electric field



## Develop theory of defect-mediated soft-breakdowns by energetic ions

### Early work in 2009

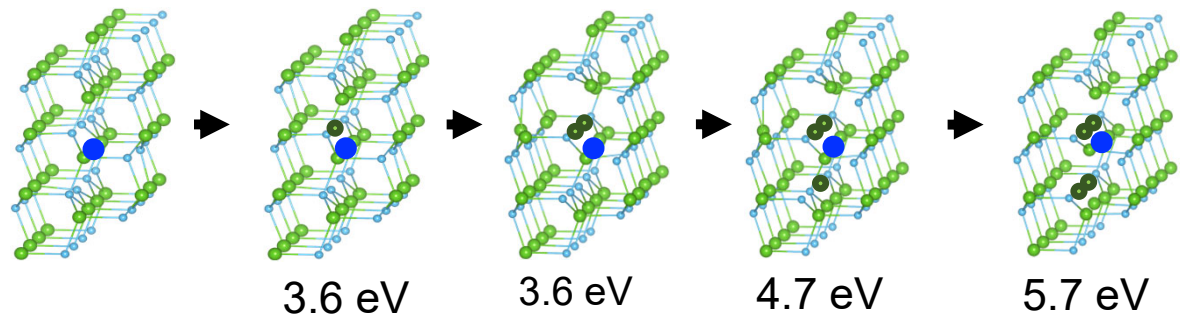
Ion-induced dielectric breakdown in Si MOSFET



### Current work:

#### ➤ Determine energetics of defect “nanowire” formation

- Nanovoid growth at vacancies in GaN (band gap 3.5 eV)



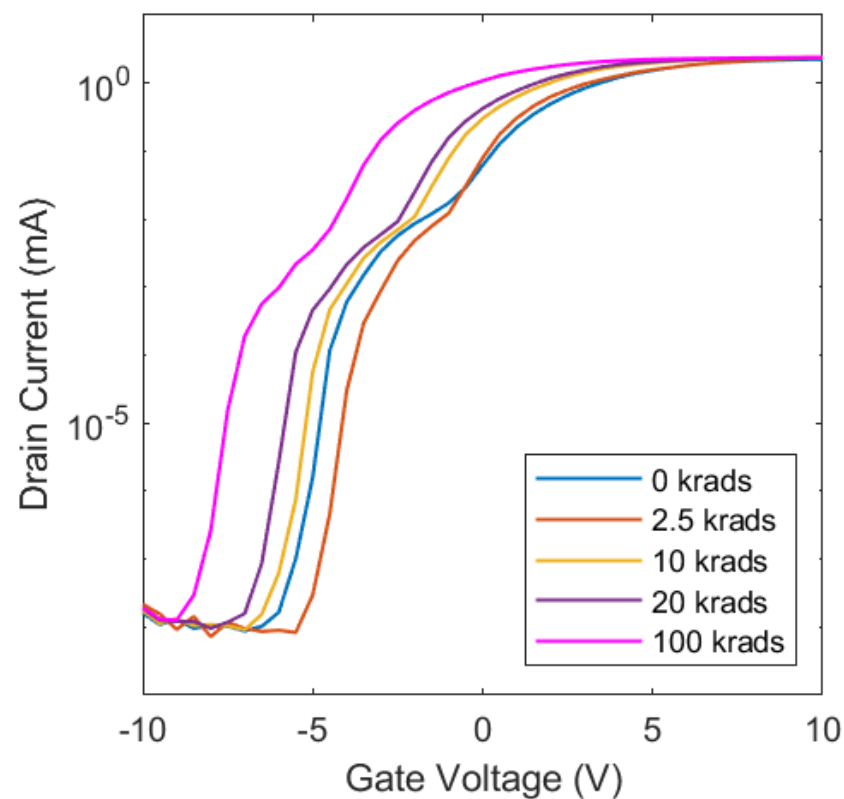
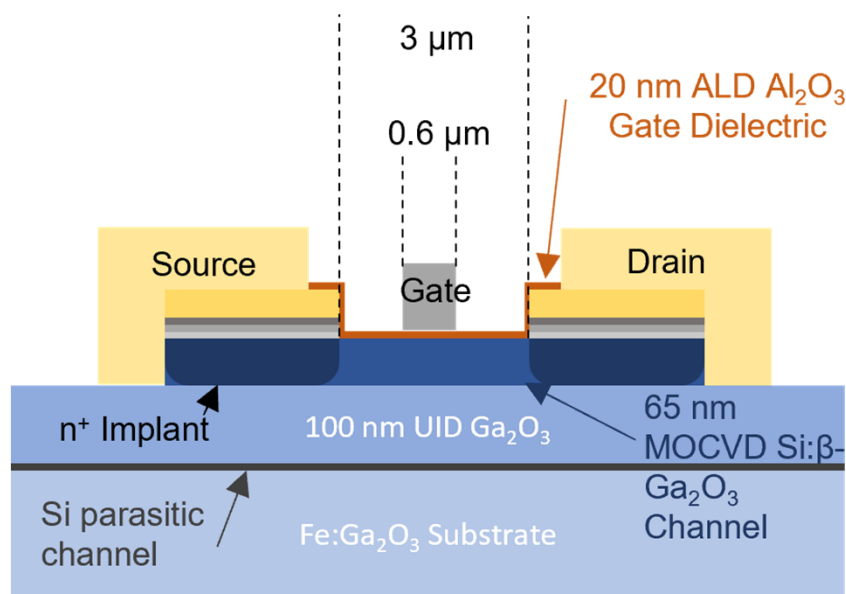
- Vacancy chain – slightly larger atom-removal energies

COMPARATIVE STUDY OF EASE OF NANOWIRE FORMATION:  
 $\beta$ -Ga<sub>2</sub>O<sub>3</sub> (most vulnerable) → AlN → GaN → SiC (least vulnerable)

#### ➤ Use “machine-learning potentials” to study very large systems

# Total Ionizing Dose Effects on Gallium Oxide MOSFETs

Collaboration with AFRL and Sandia

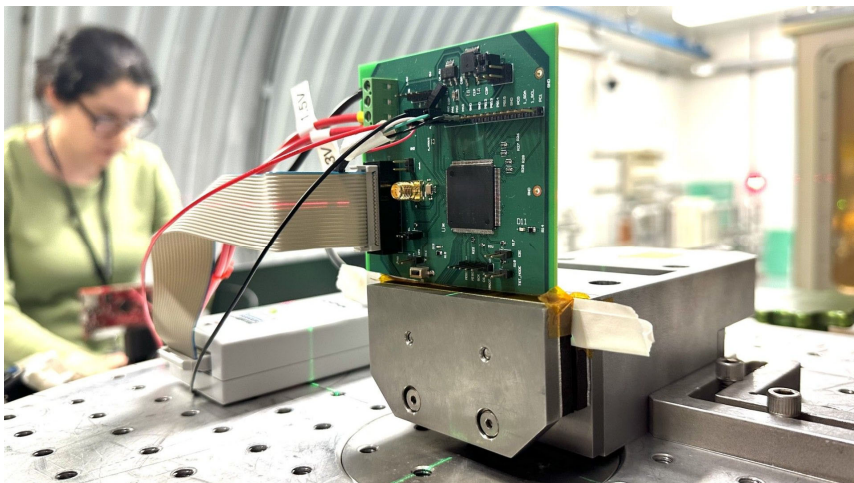


# Single-Event Functional Interrupts in Radiation-Hardened Microcontrollers

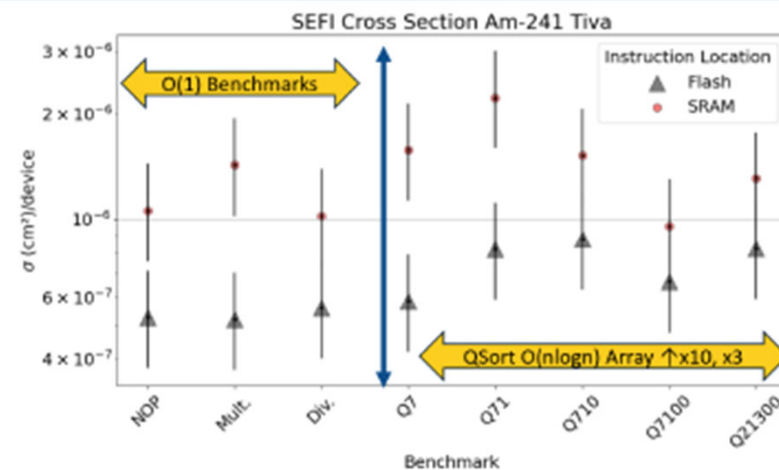
Collaboration with AFRL

[Institute For Space And Defense Electronics \(ISDE\)](#)  
[Institute For Space And Defense Electronics \(ISDE\)](#) 436 followers 436 followers 2mo • 2 months ago

How do we reliably use commercial-of-the-shelf (COTS) microcontrollers in space when radiation causes functional errors? [Vanderbilt University](#) graduate student Stefania Esquer received the Best Paper Award at the IEEE Space Computing Conference for her work to answer this important question. Stefania investigated single event functional interrupts (SEFI) in ARM microcontrollers using beam time on a proton accelerator at the Mayo Clinic. A follow-on experiment at the NASA Space Radiation Laboratory (NSRL) heavy ion accelerator was awarded by the DoD DeCPT program. She also received the Air Force Research Lab (AFRL) Outstanding Scholar Award for contributions to this topic during her internship in Albuquerque.



## Results alpha particles COTS (Tiva)



Stefania started in radiation effects research by getting involved in the [SCALE \(Scalable Asymmetric Lifecycle Engagement\)](#) Program.





# Vanderbilt Radiation Test Capabilities

**Close collaboration with other COE groups**

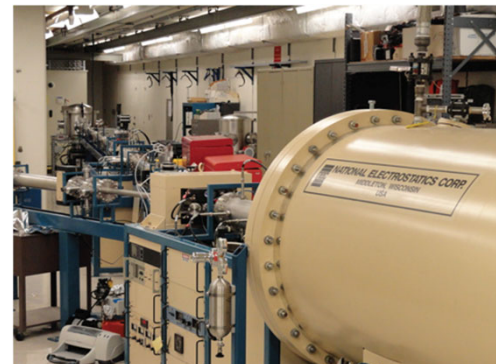
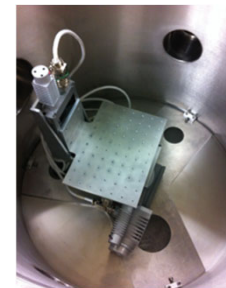


## Facilities and Equipment

- Pelletron accelerator with vacuum test chamber
  - 250 keV to 4 MeV protons
  - 500 keV to 6 MeV alphas
  - 14 MeV oxygen
  - 16 MeV chlorine
- ARACOR 4100 10 keV x-ray irradiator
- Three Cs-137 irradiators
- Low temperature dewar
- Alpha and fission fragment button sources
- Two-photon absorption laser testing for single-event effects
- Array of test & measurement equipment, from DC to 50 GHz

## Applications

- Emerging technologies
- Mechanisms studies
- Device/process characterization
- Degraded parameter extraction
- Parts evaluation
- Device & circuit simulations
- SPICE model development
- Integrated circuit design (RHBD, etc.)



## Extensive Off-site Experience

- Argonne National Laboratory
- Boeing Radiation Effects Laboratory
- Brookhaven National Laboratory
- Idaho Accelerator Center
- Indiana University
- ISIS/Rutherford Appleton Laboratory
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- Michigan State University
- NSWC Crane
- Sandia National Laboratories
- Texas A&M University
- The Svedberg Laboratory
- TRIUMF
- University of California Davis



VANDERBILT  
UNIVERSITY

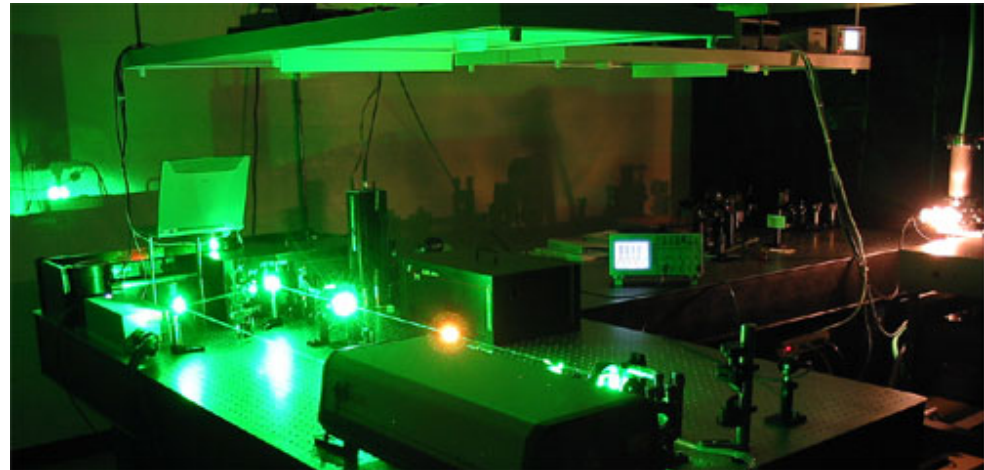
# Single-Event Effects Pulsed Laser Testing

Enabled by AFOSR/DURIP support



Ti/Sapphire pulsed laser system

- Tunable:  $200 \text{ nm} \leq \lambda \leq 10 \text{ }\mu\text{m}$  allowing TPA or SPA
- Current beamline optics support  $300 \text{ nm} \leq \lambda \leq 2600 \text{ nm}$
- 1 kHz pulse repetition rate
- Adjustable pulse energy:  $1 \text{ }\mu\text{J}$  to  $100 \text{ }\mu\text{J}$  with individual pulse width and energy measurements



- Optics provide near-IR light source to illuminate target and reflect light to IR camera for imaging and laser spot positioning.
- Two custom high-precision stages focus beam at variable z depths in the die and perform automated line, planar x-y, x-z, y-z and volumetric x-y-z scans.
- Data collected with LeCroy LabMaster 36 GHz 8-channel oscilloscope



# Workforce development



- COE collaborates with SCALE
  - Led by Purdue
  - Vanderbilt (Mike Alles) leads the Radiation-Hardened Microelectronics technical vertical
  - 29 total universities, 19 universities in RHM

## ***Radiation Hardened Microelectronics SCALE Institutions:***

