Defense Threat Reduction Agency
8725 John J. Kingman Road, MS
6201 Fort Belvoir, VA 22060-6201

DTRA-TR-22-108

TECHNICAL REPORT

WMD Radiation Effects on Vertical GaN Materials, Junctions, and Interfaces

August 2022

HDTRA1033274

Prepared by: Todd Weatherford

Naval Postgraduate School CA 93943

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	3. DATES COVERED END DATE
08-2022	Final Report	02-2017	09-2021

4. TITLE AND SUBTITLE
WMD Radiation Effects on Vertical GaN Materials, Junctions, and Interfaces

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
	HDTRA1033274	
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Weatherfod, Todd, R.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
1 University Circle
Monterey, CA 93943

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Defense Threat Reduction Agency 8725 John J Kingman Rd #6201 Fort Belvoir, VA 22060	DTRA	DTRA-TR-22-108

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The project aimed to accomplish the following major activities:
1) Measure photocurrent response on the impact of reduced breakdown, which provided useful constants to calculate avalanche for dose rate effects in GaN. 2) Metal Oxide structures were characterized and packaged. 3) Simulated and correlated experimental data to prompt radiation effects on vertical GaN P-N power diode structures. Investigated the impact of heavy ion and proton SEEs in vertical GaN device structures.

15. SUBJECT TERMS
GaN, Radiation Effects, Single Event Effects, SEE, Heavy Ions, Testing, Proton, Neutrons, Schottky, Diodes, PN, MOS, NRL, NPS, Dose Rate, Junctions, Interfaces

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
U	U	U	SAR	11

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
Jacob Calkins	571-616-5946

PREVIOUS EDITION IS OBSOLETE.

STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE.
Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE.
State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED.
Indicate the time during which the work was performed and the report was written.

4. TITLE.
Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER.
Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER.
Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER.
Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER.
Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER.
Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Grant/Award #: MIPR HDTRA1033274
PI Name: T.R. Weatherford
Organization/Institution: Naval Postgraduate School
Project Title: WMD Radiation Effects on Vertical GaN Materials, Junctions, and Interfaces

What are the major goals of the project?
List the major goals of the project as stated in the approved application or as approved by the agency. If the application lists milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion. Generally, the goals will not change from one reporting period to the next. However, if the awarding agency approved changes to the goals during the reporting period, list the revised goals and objectives. Also explain any significant changes in approach or methods from the agency approved application or plan.

The major goals proposed for: "WMD Radiation Effects on Vertical GaN Materials, Junctions, and Interfaces" are:

1. Measure photocurrent response – before/after displacement damage effects
2. Investigate the role of pre-existing defects encountered in a space-based environment.
3. Measure and characterize WMD radiation-induced defects
4. Simulate prompt radiation effects of vertical GaN power device structures.
5. Investigate the impact of single event effects (SEE) in vertical GaN device structures

Milestones in attaining goals in the reporting period are:

a. Fabrication of GaN Schottky diodes, GaN PN diodes, and Oxide structures. (NRL)
b. Characterization of devices before packaging (NRL)
c. Packaging of devices, NRL and commercial PNs. (NPS)
d. Characterization of packaged devices. (NPS)
e. Results from Heavy Ion and Proton experiments from Dose Rate experiments and TCAD modeling (NPS)

What was accomplished under these goals?
For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results, including major findings, developments, or conclusions (both positive and negative); and 4) key outcomes or other achievements. Include a discussion of stated goals not met. As the project progresses, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

Major Activities

Fabrication of all 3 types of structures (p-n diodes, Schottky and MOS capacitors) have been completed by NRL. Additional devices have been provided from other DoD/DoE programs. NPS has packaged structures for testing.

1. Measure photocurrent response on the impact of reduced of breakdown. This work provided useful multiplication constants to calculate avalanche for dose rate effects in GaN.

2. Metal Oxide structures have been characterized and packaged.

3. Simulated and correlated to experimental data prompt radiation effects on vertical GaN P-N power diode structures.

4. Investigate the impact of single event effects (SEE) in vertical GaN device structures. SEE heavy ion and proton experiments were performed.

Table 1 provides the progress in the second year.

	Schottky Diodes **2um UID MOCVD GaN on HVPE GaN**		PN junctions **5um UID MOCVD GaN on HVPE GaN**		MOS sidewall **1um GaN:Si on HVPE GaN**		Other tasks **Modeling Mg studies**	
Fabricated	2 of 3 runs		2 of 3 runs		1 of 3 runs		Added 2^{nd} PNs	
Packaged or TEM samples	NRL & Avogy	TEM	NRL & Avogy	TEM	NRL MOS			
Structures to:	NPS	UCB	NPS	UCB	NPS	UCB	na	UCB
Characterized prior rad	FIV,RIV, EL,SP		FIV,RIV, EL,SP (NRL & Avogy)		FIV,RIV, EL,SP			
Heavy Ions					Tx A&M			
Post Char./TEM								
Proton					Tx A&M			
Post Char./TEM								
FXR	Ongoing		Ongoing				Photocurrent, trapping modeling	
Characterized/TEM	Post char		Post char		Post char			
neutrons								
Characterized/TEM					C-V, I-V			

Table 1 – The test matrix of the components examined in this work.

In the first year the issue for fabrication was which substrate vendor to utilize. This was narrowed to using Kyma substrates in the last year.

Specific Objectives

A critical issue with all power devices in a dose rate environment is the impact of ionization over a depleted high E-field region. How much does a technology breakdown voltage need to be de-rated in a specific environment? How the power device termination is designed, and the material properties must be understood how the ionization event changes the E-fields during and after the event. Our results both measured and simulated explain what occurs and provides useful avalanche multiplication factors for designers and researchers to predict how breakdown voltages are reduced by an event.

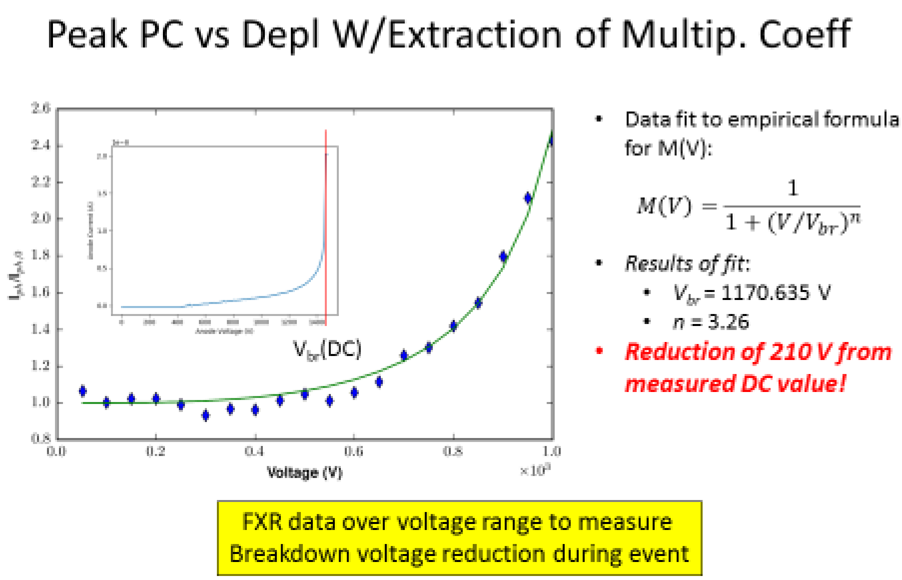


Figure 1 - Peak Photocurrent

The data in the Figure 1 above is experimental FXR measurements on a vertical GaN p-n diode. As the reverse bias is increased for equivalent dose shots the effect of avalanche multiplication is observed to the empirical equation. The exponent and a new breakdown is determined from the data. Compared to the non-irradiated DC breakdown (~1400 V) this dose environment lowered the breakdown by 15%.

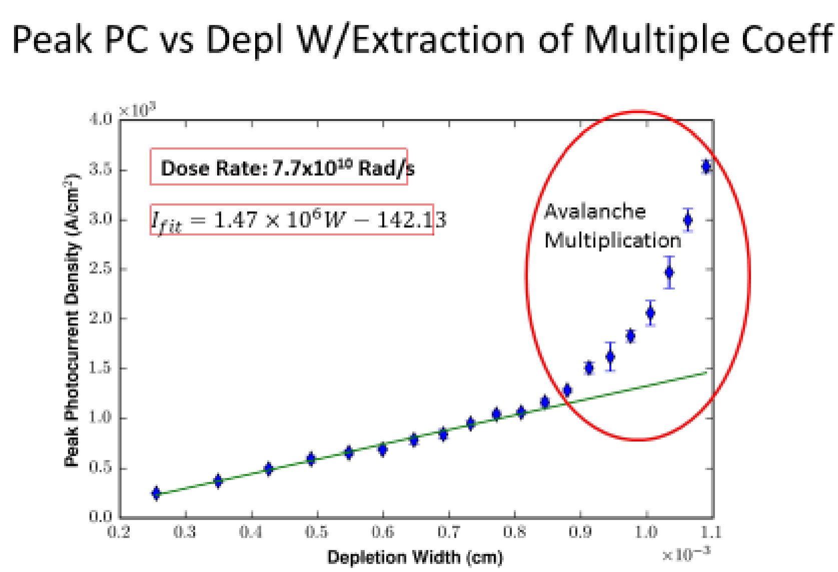


Figure 2 - Impact of avalanche on photocurrent

Even more important as the depletion width increases as reverse bias extends, the avalanche multiplication provides a considerable photocurrent gain more than the expected linear basic charge collection. Shown in Figure 2, the peak photocurrent becomes non-linear when radiation induced avalanche occurs. Note, depletion width is related to the square root of V.

Simulation of Dose rate effect in GaN PN diode

To understand how the ionizing pulse impacts the electric field of the off device, simulations were performed in Technology Computer Aided Design (TCAD) software (Silvaco).

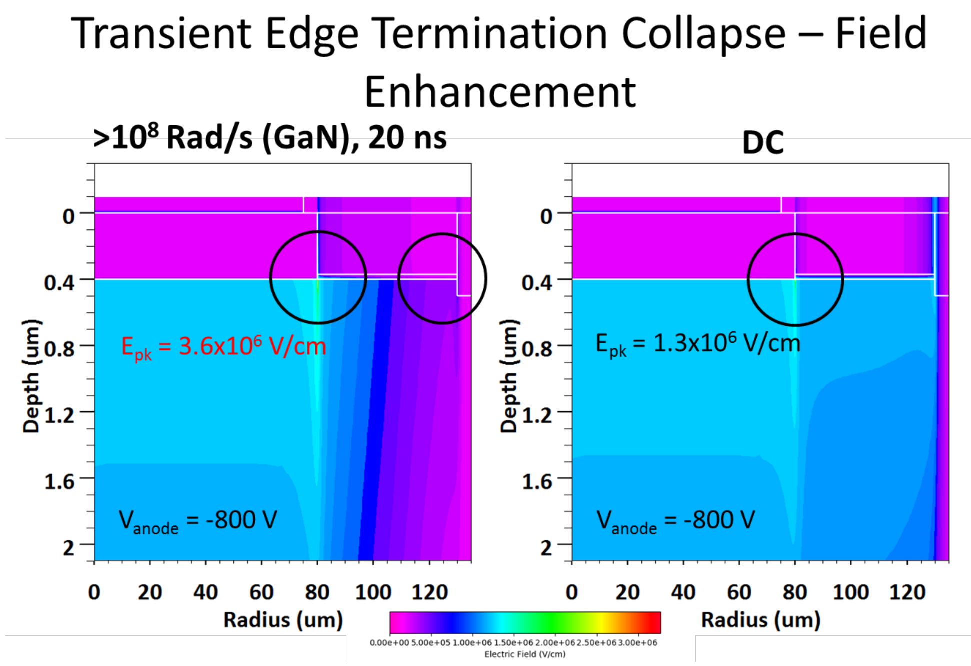


Figure 3 - Simulation of E-field due to ionizing pulse

In the Figure 3 above, collapse from a 20 ns ionizing pulse is modeled on the left image. The right image is the normal DC condition. The purpose of the termination structure (on the right of each image) is to spread out the E-field to keep the peak E-field below breakdown. However, the collapse of the termination region E-field almost triples the E-field by the end of a 20 ns ionizing pulse. Breakdown through the depletion region occurs and leakage through the termination region increases as measured in Figure 2.

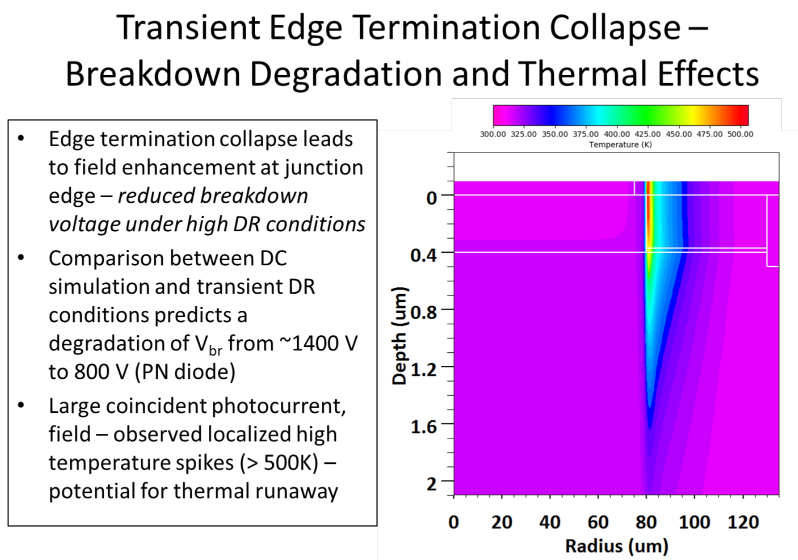


Figure 4 - Thermal effects due to collapse

An additional impact of the breakdown of the termination region (as shown in Figure 4) is the I^2R power drop in the device increases temperature which can possibly degrade the device. Gallium Nitride has an advantage over Si and SiC devices, in that the breakdown is not normally destructive to the device. We have not observed any failures in PN GaN diodes with FXR tests.

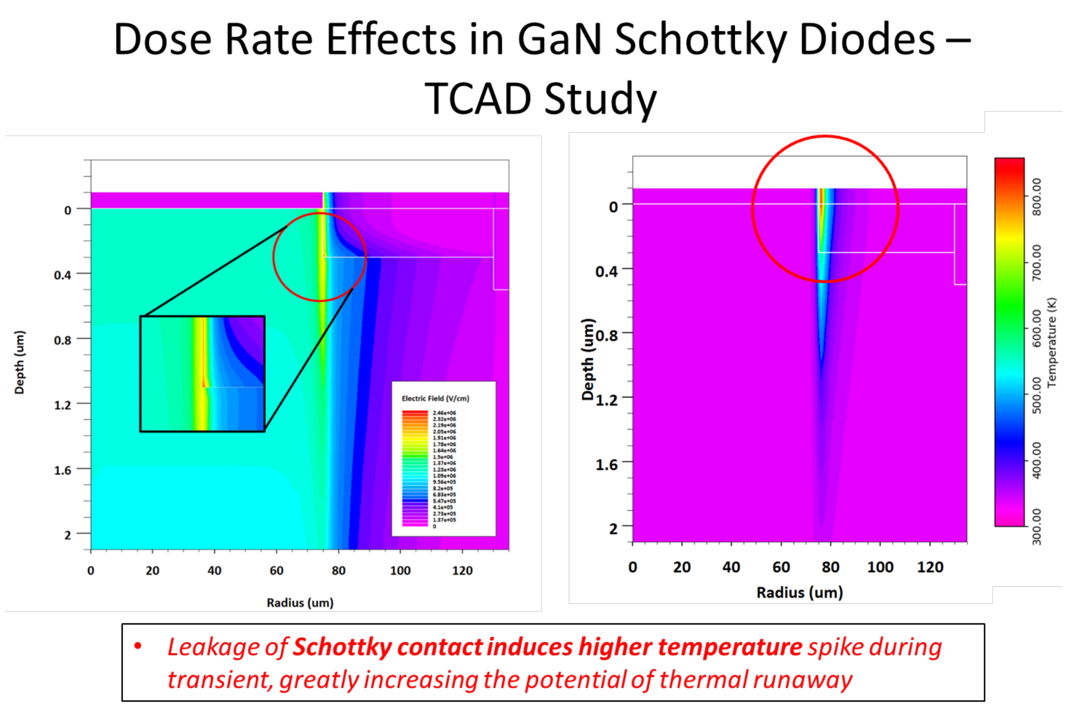


Figure 5 - TCAD simulation of a GaN Schottky diode

In Figure 5 – A TCAD simulation of a GaN schottky illustrates that because of the lower barrier height of the diode, a higher photocurrent occurs from collapse of the E-field in the termination region. This higher current due to the higher current (I) through the device creates a higher temperature than in the PN junction. In Figure 6 a measured photocurrent is shown from a FXR pulse. In the Schottky experiments we have had permanent failures due to FXR measurements.

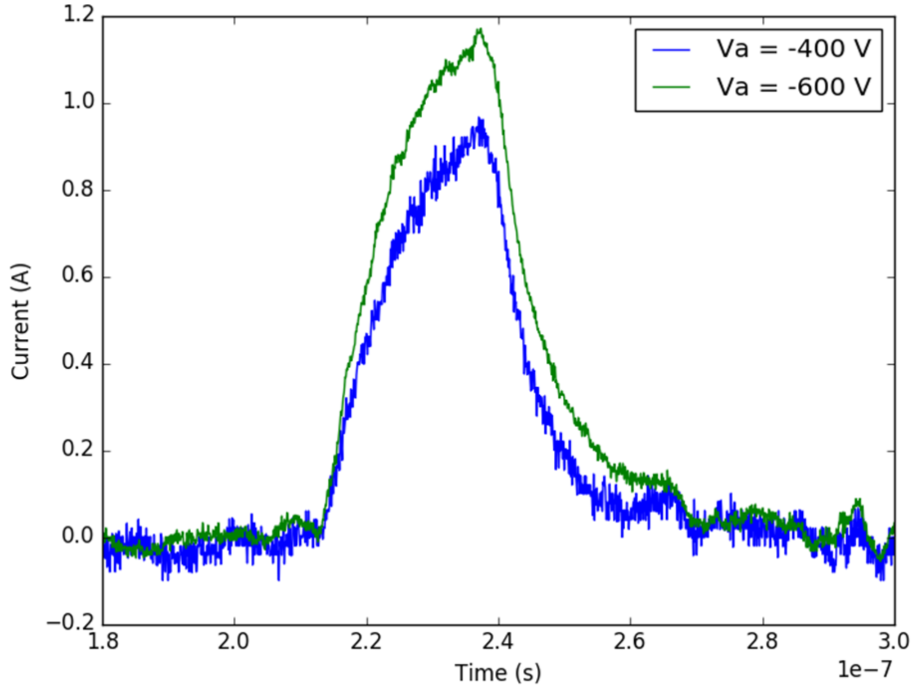


Figure 6 - Measured photocurrent of a GaN Schottky diode

Further studies need to be performed on Schottky devices. One aspect is that the Schottky diodes tested were not as mature in process technology as the PN diodes were. Further testing will also examine effects of displacement damage on these devices (and Capacitors on GaN).

Heavy Ion and Proton studies on GaN/ZrO_2 capacitors

The use of ZrO2 as a gate oxide in GaN power vertical MOSFETs may be promising to obtain enhancement devices [And16]. IN the last year of the work Gallium Nitride Zirconium oxide metal oxide semiconductor capacitors were exposed to a 40MeV proton beam and a 15MeV Argon heavy ion beam of radiation. Characterization of each device was done by NPS students using an Agilent B1500A, switch matrix, custom-printed circuit board while using a LabVIEW program to analyze the Capacitance-Voltage (C-V), Capacitance-Frequency (C-F), and Current-Voltage (I-V) measurement prior to and post exposure. Each reticle's C-V measurement and its hysteresis was then compared pre- and post-exposure for effects. Testing concluded with a time dependent dielectric breakdown analysis. Results show that radiation exposure shifts the capacitance of the device and affects the hysteresis in its C-V measurement. Initial time dependent dielectric breakdown data shows that devices exposed to certain fluences of radiation will extend the time it takes before oxide breakdown.

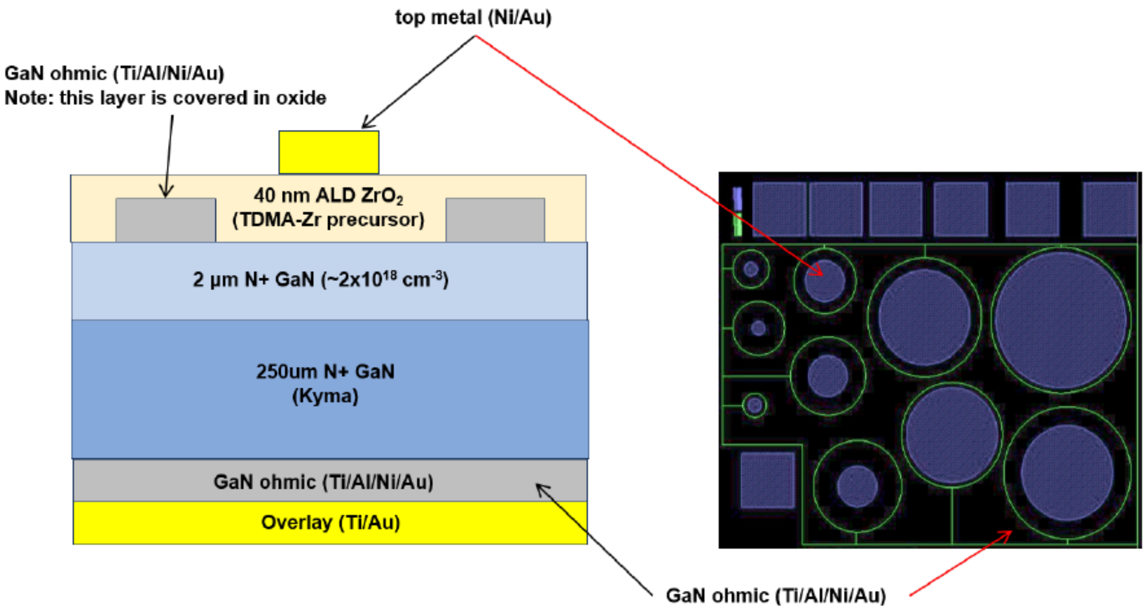


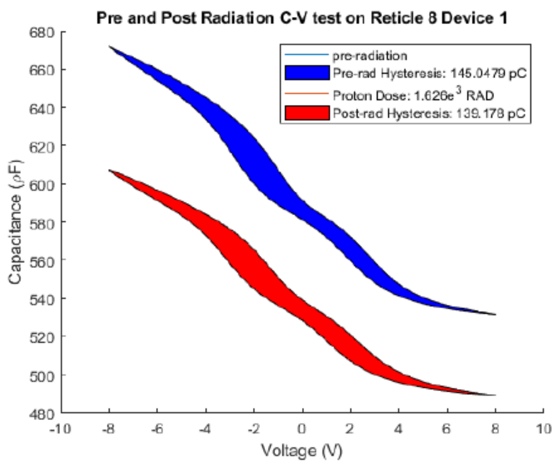
Figure 7 - Cross-section of GaN MOSCAPs used for radiation exposure testing.[Rea20]

The device capacitance and current characteristics were measured before and after irradiations over frequency and voltage as shown in Table 2.

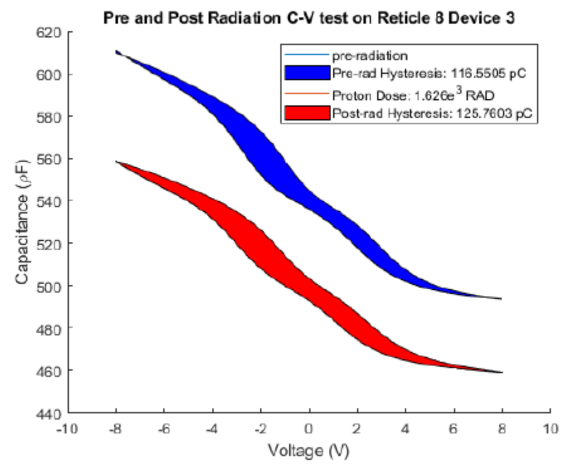
Capacitance-Frequency Measurement				
	Sweep mode	Bias Voltage	Start Frequency	Stop Frequency
Measurement 1	Single	0 Vdc	1 kHz	500 kHz
Measurement 2	Single	2 Vdc	1 kHz	500 kHz
Measurement 3	Single	-2 Vdc	1 kHz	500 kHz
Capacitance-Voltage Measurement				
	Sweep mode	Frequency	Start Voltage	Stop Voltage
Measurement 1	Double	500kHz	-6 V	6 V
Measurement 2	Double	500kHz	-7 V	7 V
Measurement 3	Double	500kHz	-8 V	8 V
Measurement 4	Double	500kHz	-9 V	9 V
Measurement 5	Double	500kHz	-10 V	10 V
Current-Voltage Measurement				
	Sweep mode	Current Compliance	Start Voltage	Stop Voltage
Measurement 1	Double	3 mA	-8 V	8 V

Table 2 - Tables showing each measurement used during characterization. [Rea20]

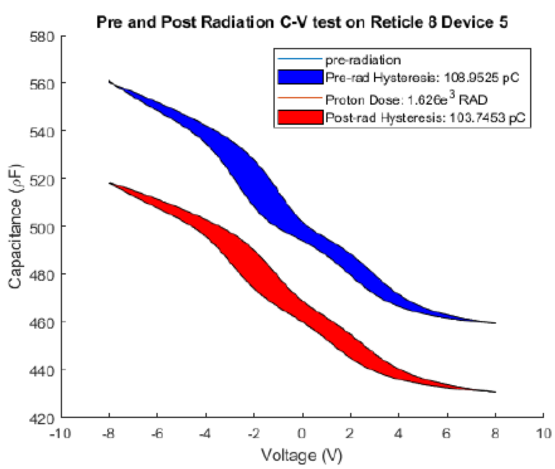
During heavy ion irradiation, devices were biased to provide E-field across the oxides. Devices were exposed over three different bias voltages of $10.8V$, $11V$ *and* $11.2V$ over a total exposure time of 1280 seconds. Devices under proton irradiation were not biased, but shorted. Proton results are shown in Figure 8. The area in each hysteresis loop is proportional to the charge in the oxide.



(a)



(b)



(c)

Figure 8 - a)-c) shows reticle “8” devices pre- and post-proton dose with short radiation C-V measurements with area of hysteresis.

Under proton irradiation, capacitance decreased with shorted devices, and devices biased showed an increase of capacitance. Figure 9 are results of biased capacitors.

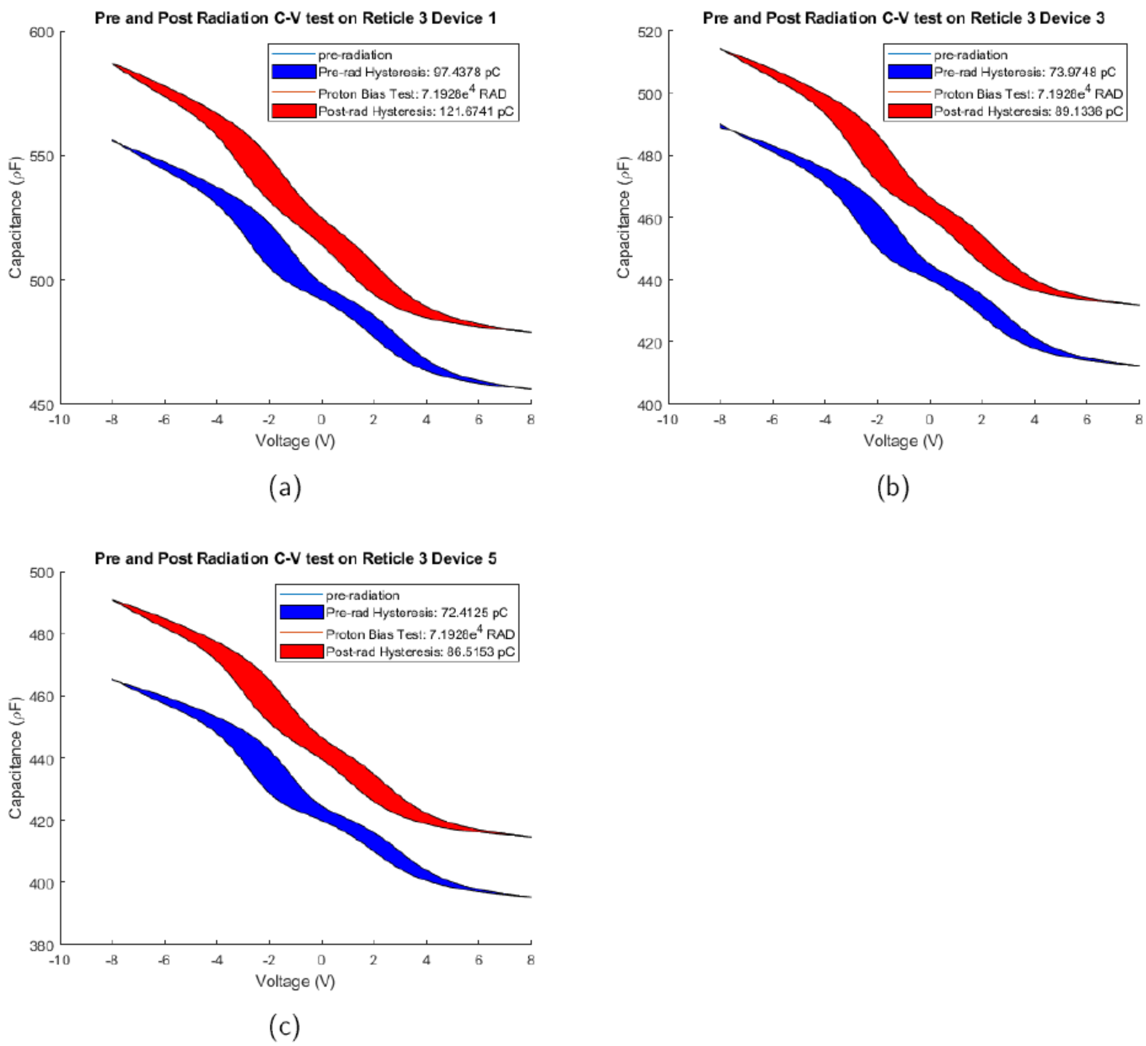


Figure 9 – Results of biased capacitors under proton irradiation.

Heavy Ion irradiated (Argon) resulted in increased capacitance as shown in Figure 10.

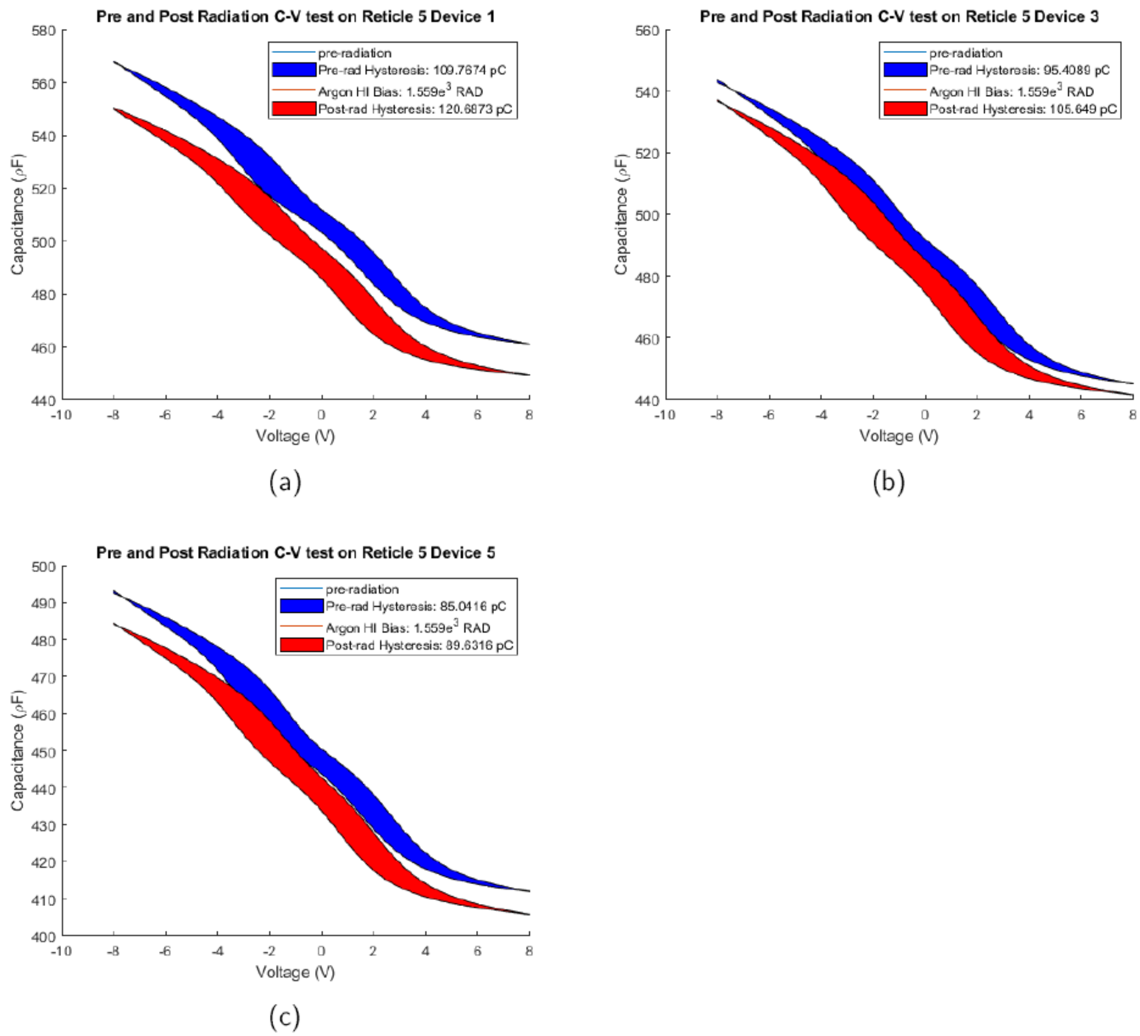


Figure 10 - a) - c) shows reticle 5 devices pre- and post-heavy ion with positive bias radiation C-V measurements with area of hysteresis.

Time dependent dielectric breakdown (TDDB) measurements were performed on unirradiated, proton irradiated and heavy ion irradiated devices. TDDB measurements exhibited different behavior than expected. Instead of showing a decrease in oxide breakdown time, certain irradiated devices showed an increased survival at high stress of the device, with some lasting two to four times longer than devices with no exposure. TDDB measurements also showed more sensitivity to lower bias voltages than higher bias voltages. It appears that this data has no correlation with TDDB under stress bias [Rea20].

What opportunities for training and professional development has the project provided?
If the research is not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report." Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include

workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

1. Briefing to AF leadership on Dose rate research at NPS to support short course development at NPS to educate senior AF leadership on strategic nuclear technical issues.
2. NPS classes (2) utilized FXR facilities to test the components in related to this project. (16 students).
3. 3 NPS master theses on FXR and neutron radiation effects funded by this effort (LT Clemmer, LT Reasonblasch, LT Miller)
4. 1 USNA midshipman intern at NPS (June 2019).

Professional Development

1. Prof. Weatherford, Dr. Anderson attended WOCSEMMAD, Feb 2018

How have the results been disseminated to communities of interest?
If there is nothing significant to report during this reporting period, state "Nothing to Report." Describe how the results have been disseminated to communities of interest. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these research activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

June 2019 DTRA review presentation

Feb 2019 – WOCSEMMAD presentation

References

[And16] - Travis J. Anderson et al, Appl. Phys. Express, vol9, p071003, 2016

[Rea20] - Reasoner Blasch, Connor M. "ANALYSIS OF RADIATION EFFECTS ON GALLIUM NITRIDE ZIRCONIUM OXIDE METAL OXIDE SEMICONDUCTOR CAPACITORS", Master's thesis Sept 2020 Naval Postgraduate School, Monterey, CA; http://hdl.handle.net/10945/66129