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4. TITLE AND SUBTITLE Final Report: Fundamental Studies of Growth and Processing of III-N-based deep UV solar-blind back-side-illuminated Separate Absorption and Multiplcation	5a. CONTRACT NUMBER W911NF-15-1-0489
	5b. GRANT NUMBER
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Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Russell Dupuis
UU	UU	UU	UU		19b. TELEPHONE NUMBER 404-385-6094

RPPR Final Report
as of 12-May-2021

Agency Code: 21XD

Proposal Number: 66737EL | **Agreement Number: W911NF-15-1-0489**

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DUNS Number: 097394084 EIN: 580603146
Report Date: 13-Feb-2021 Date Received: 10-May-2021
Final Report for Period Beginning 14-Aug-2015 and Ending 13-Nov-2020
Title: Fundamental Studies of Growth and Processing of III-N-based deep UV solar-blind back-side-illuminated Separate Absorption and Multiplcation
Begin Performance Period: 14-Aug-2015 **End Performance Period:** 13-Nov-2020
Report Term: 0-Other

Submitted By: Russell Dupuis Email: russell.dupuis@ece.gatech.edu
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 6 **STEM Participants:** 8

Major Goals: This program explores the MOCVD growth and properties of materials and device structures for UV and deep-ultraviolet (DUV) solar-blind (SB) avalanche photodiodes (APDs) capable of Geiger-mode (GM) operation and fabricated in the wide-bandgap AlInGaN materials system. We are exploring many fundamental aspects related to the realization of optimized III-N DUV GM-APDs. As an overview, we have structured two Tasks in this program
Task 1: Exploration of optimized MOCVD growth conditions for III-N DUV APD heterostructures
Task 2: Exploration of the impact of device design and processing of APD through comparative performance evaluation of devices

Accomplishments: See PDF in the Upload Section.

Training Opportunities: During the course of this program, eight Georgia Tech PhD graduate students and five Post Docs in the School of ECE worked on this project. This includes one female ECE PhD student who graduated and then worked as a Post Doc in Dupuis' group and is now a Post Doc at Oak Ridge National Labs and will soon move to a permanent research staff position at the US Army Research Laboratory in Adelphi MD. In addition, two of the current PhD students currently working on this project are female, one in ECE and one in Materials Science and Engineering.

Results Dissemination: In the period covered in this program, we have published 12 papers in refereed technical journals and 30 presentations at national and international conferences.

Honors and Awards: Dupuis has received the following awards in this period:
1. Elsevier Materials Today Materials Innovation Award (2019).
2. International SSL Alliance Award of Outstanding Achievement for Global Solid State Lighting Development (2016).
3. National Academy of Engineering Charles Stark Draper Engineering Award (2015). With I. Akasaki, M. G. Craford, N. Holonyak, Jr., and S. Nakamura; Citation: "for the invention, development, and commercialization of materials and processes for light-emitting diodes (LEDs)." Dupuis' contribution was described as: "Russell Dupuis developed and refined a process called metal organic chemical vapor deposition (MOCVD) in 1977, which enabled production of high-brightness LEDs. Dupuis' MOCVD technology is the basis of virtually all production of high-brightness LEDs, laser diodes, solar cells, and high-speed optoelectronic (light controlling) devices."
4. The Institute of Electrical and Electronics Engineers (IEEE) Life Fellow Award (2015).

Protocol Activity Status:

Technology Transfer: We have interacted with the US Army Research Laboratory group under Dr. Michael Wraback to do some time-resolved characterization studies. Also, related NASA-funded Phase I and II SBIRs with Magnolia Optical Technologies have also been won due to the successful work performed on this project.

PARTICIPANTS:

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Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
National Academy Member: Y

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

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National Academy Member: N

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Photonics Technology Letters
Publication Identifier Type: DOI Publication Identifier: 10.1109/LPT.2017.2779798
Volume: 30 Issue: 2 First Page #: 181
Date Submitted: 3/8/18 12:00AM Date Published: 1/1/18 10:00AM
Publication Location:
Article Title: p-i-p-i-n Separate Absorption and Multiplication Ultraviolet Avalanche Photodiodes
Authors: Mi-Hee Ji, Jeomoh Kim, Theeradetch Detchprohm, Yuanzheng Zhu, Shyh-Chiang Shen, Russell D. Dup
Keywords: MOCVD, III-N, UV, avalanche photodiodes
Abstract: Front-illuminated GaN-based separate absorption and multiplication (SAM) ultraviolet (UV) avalanche photodiodes (APDs) with various photon detection areas are demonstrated grown by metalorganic chemical vapor deposition on bulk GaN native substrates with low dislocation density. By adopting a front-illuminated UV-APD structure with a thin AlGaN window layer, no additional etching of the substrate for the reduction of strong UV absorption is required. The epitaxial layer structure of the p-i-p-i-n SAM UV-APDs consists of a Mg-doped p-Al0. 05Ga0.95N window layer to minimize UV absorption at the top surface region and a Mg-graded p-GaN charge layer to serve as a field-termination layer. The onset point of the breakdown voltage (VBR) is around 73 V for all SAM-APDs with different mesa areas ranging from 1963 to 10 000 ?m2, which is a lower VBR than the typical p-i-n UV-APDs with the similar thickness of undoped layer, where the photon absorption and multiplication processes take place simul
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Photonics Technology Letters
Publication Identifier Type: DOI Publication Identifier: 10.1109/LPT.2016.2580038
Volume: 28 Issue: 19 First Page #: 2015
Date Submitted: 3/8/18 12:00AM Date Published: 10/1/16 8:00AM
Publication Location:
Article Title: Uniform and Reliable GaN p-i-n Ultraviolet Avalanche Photodiode Arrays
Authors: Mi-Hee Ji, Jeomoh Kim, Theeradetch Detchprohm, Russell D. Dupuis, Ashok K. Sood, Nibir K. Dhar, Ja
Keywords: MOCVD, III-N, GaN, avalanche photodiodes
Abstract: GaN p-i-n ultraviolet avalanche photodiodes (UV-APDs) were fabricated from epitaxial structures grown on low-dislocation-density free-standing GaN substrates to form 4×4 UV-APD arrays with a device size of 75×75 ?m2. The devices in the UV-APD array showed a uniform and reliable distribution of breakdown voltage (VBR) and leakage current density. The average VBR of the 16 devices in one of the UV-APD arrays was 96±0.6 V, and the average dark current density (JR_Dark) and photocurrent density (JR_Photo) were measured to be (6.5±1.8)×10?7 and (5.7±1.1)×10?6 A/cm2 at the reverse bias voltage of VR = 48 V (50% of the average onset point of VBR), respectively. The reliable device performance was confirmed by performing multiple reverse bias I–V scans for the selected devices in the UV-APD array. We also observed the significantly enhanced spectral responsivity from the 142 to 5485 mA/W due to the strong carrier impact ionization at high reverse bias.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: IEEE Photonics Technology Letters
Publication Identifier Type: DOI Publication Identifier: 10.1109/LPT.2015.2388552
Volume: 27 Issue: 6 First Page #: 642
Date Submitted: 3/8/18 12:00AM Date Published: 3/1/15 5:00AM
Publication Location:
Article Title: AlxGa1-xN Ultraviolet Avalanche Photodiodes with Avalanche Gain Greater Than 105
Authors: Jeomoh Kim, Mi-Hee Ji, Theeradetch Detchprohm, Jae-Hyun Ryou, Russell D. Dupuis, Ashok K. Sood,
Keywords: MOCVD, III-N, UV, Avalanche Photodiodes, APDS
Abstract: Ultraviolet (UV) avalanche photodiodes (APDs) based on Alx Ga1?xN wide-bandgap semiconductor alloys (x = 0.05) are reported. The epitaxial structure was grown by metalorganic chemical vapor deposition on a GaN substrate having a low dislocation density. Step graded n-type Si-doped AlxGa1?xN layers (x = 0 and 0.02) were introduced instead of a thick n-Al0.05Ga0.95N:Si layer to minimize strain-induced defects and crack formation, resulting in reduced leakage current densities of the devices with various circular mesa diameters. Under UV illumination at ? = 280 nm, high avalanche gains greater than 1.5 × 105 were achieved at reverse biases of VR > 94 V for the APDs with mesa diameters of 30–70 ?m. In addition, significantly increased spectral responsivities of devices having a 70-?m mesa diameter was observed at reverse biases of VR > 90 V, indicating the device approaches to avalanche multiplication.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: International Journal of Engineering Research and Technology. ISSN 0974-3154 Volume 10, Number 2 (2017), pp. 129-150
Publication Identifier Type: ISSN Publication Identifier: 0974-3154
Volume: 10 Issue: 2 First Page #: 129
Date Submitted: 3/8/18 12:00AM Date Published: 10/30/17 4:00AM
Publication Location: India
Article Title: Development of High Gain GaN/AlGaN Avalanche Photodiode Arrays for UV Detection and Imaging Applications
Authors: Ashok K. Sood, John W. Zeller, Yash R. Puri, Russell D. Dupuis, Theeradetch Detchprohm, Mi-Hee Ji, S
Keywords: MOCVD, UV, Avalanche photodiodes,
Abstract: Sensing and imaging over ultraviolet (UV) bands has many applications for defense and commercial systems, as shorter wavelengths allow for increased spatial resolution, smaller pixels, and larger formats. The next frontier is to develop UV avalanche photodiode (UV-APD) arrays with high gain to demonstrate high-resolution imaging. Various GaN/AlGaN p-i-n UV-APDs have been fabricated from epitaxial structures grown by metalorganic chemical vapor deposition (MOCVD) on low dislocation density substrates. The performance characteristics of frontside-illuminated UV-APDs grown on GaN/sapphire templates were compared with UV-APDs grown on free-standing (FS) GaN substrates, where the latter demonstrated lower dark current densities for all fabricated mesa sizes, stable avalanche gains higher than 5×105, and significantly higher responsivities. In addition, UV-APD epitaxial structures were fabricated in 4×4 arrays with large detector areas, showing uniform and reliable operation.
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Journal: International Journal of Engineering Research and Technology
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Article Title: Development of High Gain GaN/AlGaN Avalanche Photodiode Arrays for UV Detection and Imaging Applications
Authors: Ashok K. Sood, John W. Zeller and Yash R. Puri, Russell D. Dupuis, Theeradetch Detchprohm, Mi-Hee
Keywords: Avalanche Photodiode, Ultraviolet, GaN, AlGaN Arrys
Abstract: Sensing and imaging over ultraviolet (UV) bands has many applications for defense and commercial systems, as shorter wavelengths allow for increased spatial resolution, smaller pixels, and larger formats. The next frontier is to develop UV avalanche photodiode (UV-APD) arrays with high gain to demonstrate high-resolution imaging. Various GaN/AlGaN p-i-n UV-APDs have been fabricated from epitaxial structures grown by metalorganic chemical vapor deposition (MOCVD) on low dislocation density substrates. The performance characteristics of frontside-illuminated UV-APDs grown on GaN/sapphire templates were compared with UV-APDs grown on freestanding (FS) GaN substrates, where the latter demonstrated lower dark current densities for all fabricated mesa sizes, stable avalanche gains higher than 5×105, and significantly higher responsivities. In addition, UV-APD epitaxial structures were fabricated in 4×4 arrays with large detector areas, showing uniform and reliable distribution of breakdown
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Publication Identifier Type: Other Publication Identifier: SPIE Proceedings
Volume: 10918 Issue: First Page #: 1091814
Date Submitted: 10/25/19 12:00AM Date Published: 2/7/19 10:00AM
Publication Location: Bellingham WA USA
Article Title: Demonstration of uniform and reliable GaN p-i-p-i-n separate-absorption and multiplication ultraviolet avalanche photodiode arrays with large detection area
Authors: M.-H. Ji, H. Jeong, M. Bakhtiary-Noodeh, S.-C. Shen, T. Detchprohm, A. K. Sood, P. P. Ghuman, S. Ba
Keywords: MOCVD, Gallium nitride, wide bandgap, APD,
Abstract: Front-illuminated GaN p-i-p-i-n separate-absorption and multiplication avalanche photodiode (SAM-APD) epitaxial structures were grown by metalorganic chemical vapor deposition (MOCVD) on n-type bulk GaN substrates and fabricated into 4×4 arrays with a large detection area of 100×100 µm2. The SAM-APD array showed a uniform distribution of dark current density of JDark<(5.1±0.8)×10-8 A/cm2 at reverse bias (VR) of 44 V except for two of them. In addition, the average onset points of breakdown voltages (VBR) of the SAM-APD array was 73.1±0.21 V, and no microplasmas were visually observed after multiple times I-V scans.
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Acknowledged Federal Support: **Y**

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Science and Innovations
Date Received: 28-Oct-2019 Conference Date: 14-May-2017 Date Published: 14-May-2017
Conference Location: San Jose, California
Paper Title: Growth and Characterization of III-N Ultraviolet Lasers and Avalanche Photodiodes by MOCVD
Authors: Mi-Hee Ji1, Yuh-Shiuan Liu1, Jeomoh Kim1, Young-Jae Park1, Theeradetch Detchprohm1, Russell D. D
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Optical Engineering + Applications
Date Received: 25-Sep-2018 Conference Date: 31-Jan-2017 Date Published:
Conference Location: San Diego, California, United States
Paper Title: Development of high gain avalanche photodiodes for UV imaging applications
Authors: M.-H. Ji, J. Kim, T. Detchprohm, R. D. Dupuis, A. Sood, N. Dhar, and J. Lewis
Acknowledged Federal Support: **Y**

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Conference Name: 59th Electron. Mat. Conf.
Date Received: 25-Sep-2018 Conference Date: 28-Jun-2017 Date Published: 28-Jun-2017
Conference Location: Notre Dame IN, USA
Paper Title: Growth and Characterization of GaN p-i-p-i-n Ultraviolet Avalanche Photodiodes
Authors: M.-H. Ji, J. Kim, T. Detchprohm, Y. Zhu, S.-C. Shen, and R. D. Dupuis
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Twelfth Int'l. Conf. Nitride Semiconductors (ICNS-12)
Date Received: 28-Oct-2019 Conference Date: 23-Jul-2017 Date Published: 23-Jul-2017
Conference Location: Strasbourg, France
Paper Title: Growth, Fabrication, and Characterization of GaN p-i-p-i-n Ultraviolet Avalanche Photodiodes
Authors: Mi-Hee Ji, Jeomoh Kim, Theeradetch Detchprohm, Yuanzheng Zhu, Shyh-Chiang Shen, and Russell D.
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 18th U.S. Biennial Workshop on Organometallic Vapor Phase Epitaxy (OMVPE-2017)
Date Received: 21-Apr-2019 Conference Date: 30-Jul-2017 Date Published: 30-Jul-2017
Conference Location: Santa Fe, NM, USA
Paper Title: GaN p-i-p-i-n Separate Absorption and Multiplication Ultraviolet Avalanche Photodiodes by Metalorganic Chemical Vapor Deposition
Authors: M.-H. Ji, J. Kim, T. Detchprohm, Y. Zhu, S.-C. Shen, and R. D. Dupuis
Acknowledged Federal Support: **Y**

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Conference Name: 2017 IEEE Electron Device and Solid-State Circuits (EDSSC '17)
Date Received: 28-Oct-2019 Conference Date: 18-Oct-2017 Date Published: 18-Oct-2017
Conference Location: Hsinchu, Taiwan
Paper Title: III-nitride optoelectronic devices for ultraviolet systems
Authors: S.-C. Shen, R. D. Dupuis, T. Detechprohm, P. D. Yoder, Y.-J. Park, M.-H. Ji, B. Chaiyasarikul, O. Morer
Acknowledged Federal Support: **Y**

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Conference Name: ICCGE-19/OMVPE-19/ISSCG 2019
Date Received: 10-Oct-2020 Conference Date: 28-Jul-2019 Date Published: 28-Jul-2019
Conference Location: Keystone, Colorado
Paper Title: MOCVD Growth of AlGaN Back-illuminated Separate-Absorption and Multiplication Ultraviolet Avalanche Photodiodes
Authors: Marzieh Bakhtiary-Noodeh, Mi-Hee Ji, Chuan-Wei Tsou, Hoon Jeong, Eliza Gazda, A. Nepomuk Otte, S
Acknowledged Federal Support: **Y**

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Conference Name: SPIE Photonics West 2019
Date Received: 10-Oct-2020 Conference Date: 04-Feb-2019 Date Published: 04-Feb-2019
Conference Location: San Francisco CA
Paper Title: Demonstration of Uniform and Reliable GaN p-i-p-i-n Separate-Absorption and Multiplication Ultraviolet Avalanche Photodiode Arrays with Large Detection Area
Authors: Russell D. Dupuis,Mi-Hee Ji, Jeomoh Kim, Hoon Jeong, Marzieh Bakhtiary-Noodeh, Shyh-Chiang Shen
Acknowledged Federal Support: **Y**

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Conference Name: Seventh International Symposium of Growth of III-Nitrides (ISGN-7), Warsaw Poland
Date Received: 10-Oct-2020 Conference Date: 06-Aug-2018 Date Published: 11-Aug-2018
Conference Location: Warsaw Poland
Paper Title: Growth and Device Characterization of III-N Deep-Ultraviolet Avalanche Photodiodes and Arrays
Authors: M.-H. Ji, H. Jeong, M. Bakhtiary-Noodeh, J. Kim, T. Detchprohm, S.-C. Shen, P. Ghuman, S. Babu, A. K
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: US Workshop on the Physics and Chemistry of II-VI Materials
Date Received: 10-Oct-2020 Conference Date: 22-Oct-2018 Date Published: 25-Oct-2018
Conference Location: Pasadena CA
Paper Title: High Performance Ultraviolet Avalanche Photodiode Detector Technologies
Authors: A. K. Sood, J. W. Zeller, and R. D. Dupuis
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE Photonics West OPTO
Date Received: 10-Oct-2020 Conference Date: 04-Feb-2019 Date Published: 07-Feb-2019
Conference Location: San Francisco CA
Paper Title: Demonstration of Uniform and Reliable GaN p-i-p-i-n Separate-Absorption and Multiplication Ultraviolet Avalanche Photodiode Arrays with Large Detection Area,
Authors: R. D. Dupuis, M.-H. Ji, J. Kim, H. Jeong, M. Bakhtiary-Noodeh, S.-C. Shen, T. Detchprohm, A. K. Sood,
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE OP109 UV and Higher Energy Photonics: from Materials to Applications,
Date Received: 28-Oct-2019 Conference Date: 11-Aug-2019 Date Published: 16-Aug-2019
Conference Location: San Diego CA
Paper Title: III-Nitride Emitters and Detectors for UV Optoelectronic Applications
Authors: R. D. Dupuis, T. Detchprohm, M.-H. Ji, M. Bakhtiary-Noodeh, H. Jeong, P. Chen, S.-C. Shen, C.-W. Tsc
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Conference Name: 19th US Workshop on Organometallic Vapor Phase Epitaxy (OMVPE-18)
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Conference Location: Keystone, Colorado
Paper Title: MOCVD Growth of AlGaN Back-illuminated Separate-Absorption and Multiplication Ultraviolet Avalanche Photodiodes
Authors: M. Bakhtiary-Noodeh, M.-H. Ji, C.-W. Tsou, H. Jeong, E. Gazda, A. N. Otte, S.-C. Shen, T. Detchprohm
Acknowledged Federal Support: **Y**

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Conference Name: 61st Electronic Materials Conference (EMC 2019)
Date Received: 28-Oct-2019 Conference Date: 26-Jun-2019 Date Published: 28-Jun-2019
Conference Location: University of Michigan, Ann Arbor, MI
Paper Title: Growth and Characterization of AlGaN p-i-n-i-n Separate-Absorption and Multiplication Ultraviolet Avalanche Photodiodes
Authors: M. Bakhtiary-Noodeh, M.-H. Ji, H. Jeong, T. Detchprohm, and R. D. Dupuis
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: SPIE 11530, Sensors, Systems, and Next-Generation Satellites XXIV
Date Received: 29-Oct-2020 Conference Date: 23-Sep-2020 Date Published: 23-Sep-2020
Conference Location: Online Only
Paper Title: GaN-AlGaN avalanche photodiode detector technology for high performance ultraviolet sensing applications
Authors: A. Sood, J. Zeller, P. Ghuman, S. Babu, and R. Dupuis
Acknowledged Federal Support: **Y**

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Conference Name: Conference on Lasers and Electro-Optics (CLEO) 2020
Date Received: 10-Oct-2020 Conference Date: 11-May-2020 Date Published: 11-May-2020
Conference Location: virtual conference
Paper Title: Low-Noise GaN p-i-n Avalanche Photodiodes for Ultraviolet Applications Using an Ion-Implantation Isolation Technique
Authors: Minkyu Cho, Hoon Jeong, Chuan-Wei Tsou, Marzieh Bakhtiary-Noodeh, Theeradetch Detchprohm, Rus
Acknowledged Federal Support: **Y**

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Conference Name: 62nd Electronic Materials Conference (EMC 2020)
Date Received: 10-Oct-2020 Conference Date: 24-Jun-2020 Date Published: 24-Jun-2020
Conference Location: Virtual conference
Paper Title: Homojunction GaN p-i-n Ultraviolet Avalanche Photodiodes Using Ion-Implantation Isolation
Authors: 3. Marzieh Bakhtiary-Noodeh, Minkyu Cho, Chuan-Wei Tsou, Hoon Jeong, Shyh-Chiang Shen, Thee
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 62nd Electronic Materials Conference (EMC 2020)
Date Received: 10-Oct-2020 Conference Date: 24-Jun-2020 Date Published: 24-Jun-2020
Conference Location: Virtual conference
Paper Title: Geiger-mode Operation of Gallium Nitride p-i-n Avalanche Photodiodes and Histogram Fitting Measurement
Authors: Hoon Jeong, Eliza A. Gazda, Mi-Hee Ji, Minkyu Cho, Marzieh Bakhtiary-Noodeh Theeradetch Detchpro
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Georgia Institute of Technology
Date Received: 25-Sep-2018 Completion Date: 3/23/18 4:55PM
Title: GROWTH, FABRICATION, AND CHARACTERIZATION OF III-NITRIDE SEMICONDUCTORS FOR HIGH-PERFORMANCE ULTRAVIOLET AVALANCHE PHOTODIODES BY METALORGANIC CHEMICAL VAPOR DEPOSITION
Authors: Mi-Hee Ji
Acknowledged Federal Support: **Y**

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RPPR Final Report
as of 12-May-2021

I certify that the information in the report is complete and accurate:
Signature: Russell Dupuis
Signature Date: 5/10/21   5:02PM

Final Progress Report, August 2020
Fundamental studies of growth and processing of AlGaN-based deep-UV solar-blind back-side-illuminated separate absorption and multiplication avalanche photodiodes

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This program explores the MOCVD growth and properties of materials and device structures for UV and deep-ultraviolet (DUV) solar-blind (SB) avalanche photodiodes (APDs) capable of Geiger-mode (GM) operation and fabricated in the wide-bandgap AlInGaN materials system. We are exploring many fundamental aspects related to the realization of optimized III-N DUV GM-APDs. As an overview, we have structured two Tasks in this program

Task 1: Exploration of optimized MOCVD growth conditions for III-N DUV APD heterostructures

Task 2: Exploration of the impact of device design and processing of APD through comparative performance evaluation of devices

1. Growth of AlGaN layers for deep-UV photodiodes

In this program, we have been using our high-temperature III-N MOCVD system, i.e., a 3x2” Close-coupling showerhead (CCS) AIXTRON reactor capable of rising the surface temperature up to 1350°C and also offering a real-time tunable gap between showerhead and sample surface for AlGaN-based solar-blind deep-ultraviolet (DUV) APDs while the conventional III-N 6x2” CCS MOCVD system is focusing on GaN-based near UV (NUV) APDs. This 3x2” high-temperature MOCVD system has demonstrated high quality AlGaN MQW with low-threshold optical excitation of stimulated emission peaks ranging from 245 to 280nm. DUV The schematic device structure for our design of an AlGaN based separate-absorption-and-multiplication (SAM) *p-i-n-i-n* configuration on AlN/sapphire template and AlN substrate are shown in **Figure 1**. The alloy composition of each AlGaN layer is set to desired optimum cut-off wavelength. In our study, the $Al_xGa_{1-x}N$ epitaxial layers ($0.4< x <0.6$) were grown with two sets of composition-step-graded $Al_yGa_{1-y}N$/AlN short period superlattices (SPSLs) between AlN and $Al_xGa_{1-x}N$ as a strain-management layer. In our primary *p-i-n* APD, the absorption layer was set to be $Al_{0.60}Ga_{0.40}N$ for the target cut-off wavelength of 255nm. We utilized the optimum Si doping as reported last year while studying on the Mg optimization for *p*-AlGaN layers. Owing to back-illuminated device scheme, we can reduce the AlN mole fraction in the p-AlGaN from 0.5 to 0.4, which allows higher free hole concentration in the *p*-layer.

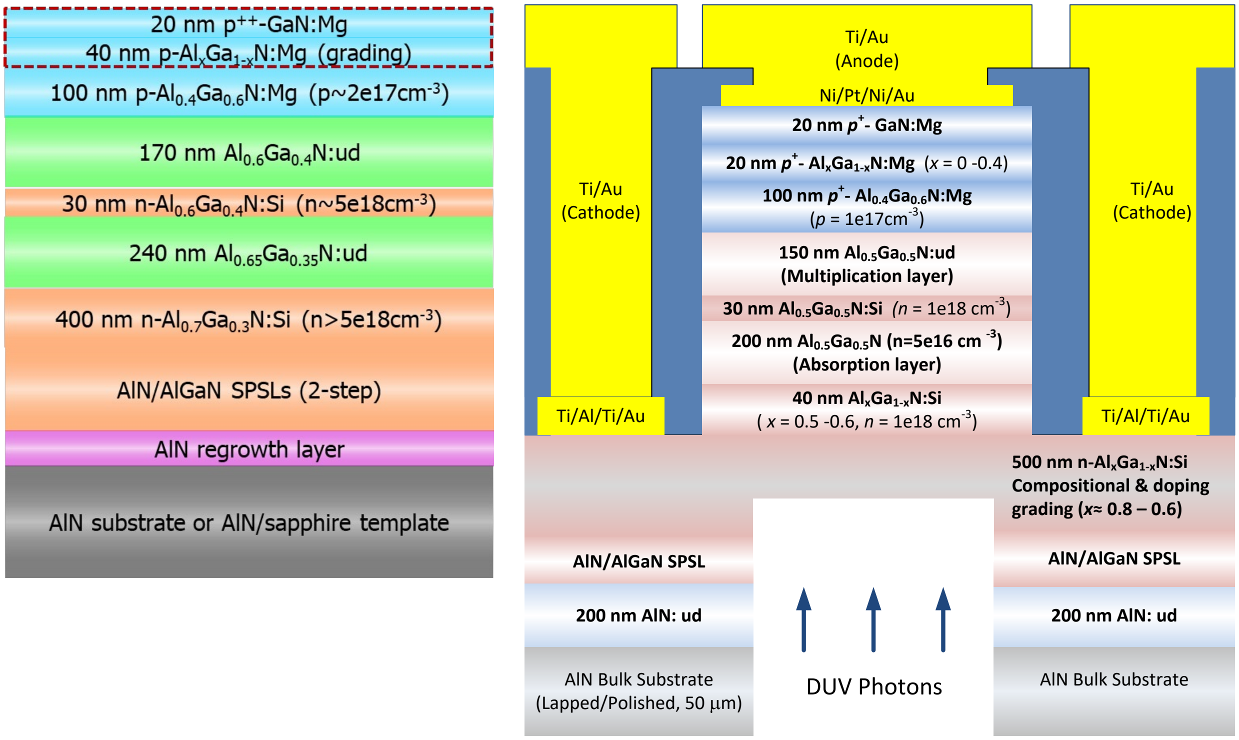


Figure 1: Epitaxial structure of an AlGaN back-illuminated solar-blind SAM *p-i-p-i-n* APD (left), and its schematic fabricated device design (right) (not in scale).

In order to verify the Si doping in the structure grown by 6x2" MOCVD system, a separate structure of *i-n-i-n* with smooth surface morphology was prepared and analyzed by SIMS as shown in **Figure 2**. [Si] profile of this sample exhibits a sharp interface as the Si doping levels in the launcher and n-contact layers were determined to be 8E18 and 5E18 cm^{-3}, respectively. These values reveal [Si] satisfying the designed doping levels. Its background impurity levels of Si, O & C in undoped AlGaN absorption and multiplication regions are 2E16, 5E15, and 1E16 cm^{-3}, respectively. The SIMS analysis of *p-i-n-i-n* AlGaN grown in this study is shown in **Figure 3.**The Si doping levels are 3E18 and 1E19 cm^{-3} for 30nm launcher and *n*-contact layers, respectively while Mg doping level is about 2-3E19 cm^{-3} as preferred. Due to rough surface morphology of *p*-layers developed over time, an interface between any two adjacent layers, however, cannot be accurately determined. In addition, O and C levels are much higher than those in *i-n-i-n* structure, i.e., 2-10E17 and 2-4E16, respectively. In order to improve the interface abruptness by maintaining a good surface morphology, we decided to further develop the DUV in our high-temp CCS MOCVD system. With a well-developed high-composition AlGaN growth, we can simply replace the first two SPSL-AlGaN layers, with $Al_{0.8}Ga_{0.2}N$ with an atomically flat surface as a platform for device growth. The AlGaN APD device growth in this system is aiming a simple *p-i-n* structure as a demonstration vehicle as shown in **Figure 4**. For AlGaN composition calibration, step graded structures have been utilized. Each individual AlGaN layer of target composition was optimized. A combined structure was then grown and analyzed for composition and material quality. An example of step graded calibration structure is shown in **Figure 5**. Partial relaxation has already been observed at the first AlGaN layer. The lower Al composition is incorporated in the layer, the bigger degree of relaxation can be expected as well as its morphology degradation. For AlGaN layers with AlN mole fraction of 0.60 down to 0.07 and *p*-GaN contact layers, a ratio of TMAl and TMGa mole supply rates have been adjusted to maintain a constant growth for any composition in between for the sake of uniform Mg doping in the graded *p*-AlGaN layer. For instance, the growth rate of the graded *p*-AlGaN and *p*-GaN layers is tuned to match that of *p*-$Al_{0.60}Ga_{0.40}N$. As shown in the table inside **Figure 5**, 3 step grading layers (AlGaN 4, 5, & 6) were individually calibrated for both growth rate and composition.

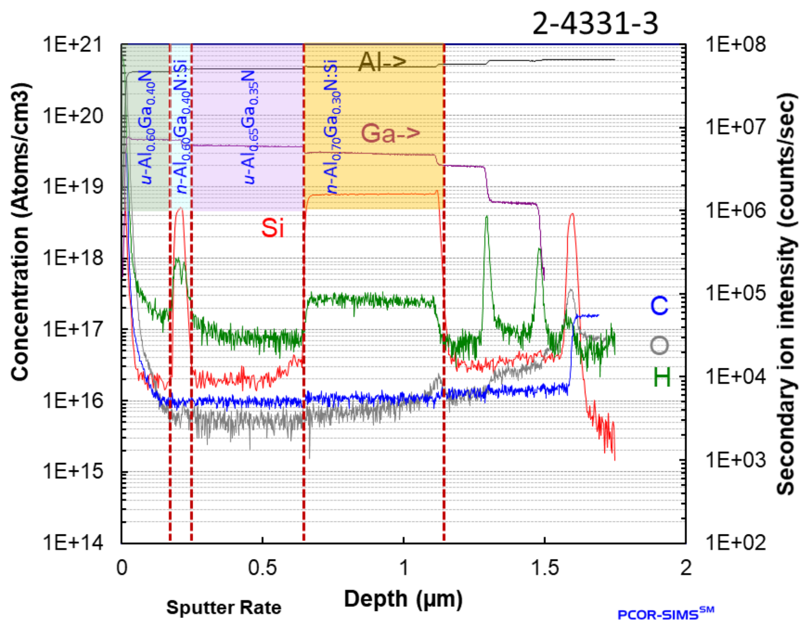


Figure 2: SIMS analysis of *i-n-i-n* sample grown AlN template. The layer sequence from left to right, is in an order of uid $Al_{0.60}Ga_{0.40}N$ multiplication, *n*-$Al_{0.60}Ga_{0.40}N$ launcher, uid-$Al_{0.65}Ga_{0.35}N$, and *n*-$Al_{0.70}Ga_{0.30}N$ contact layer**.**

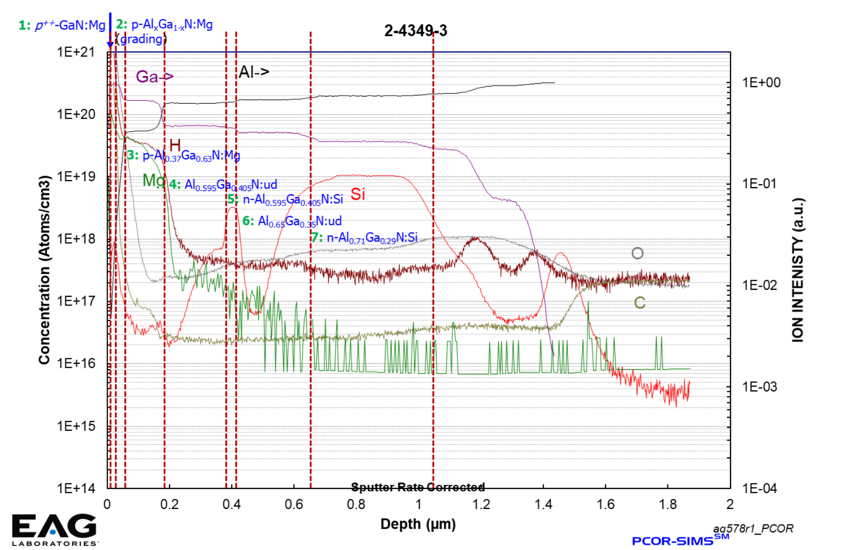


Figure 3: SIMS analysis of SAM *p-i-n-i-n* AlGaN APD grown on AlN template.

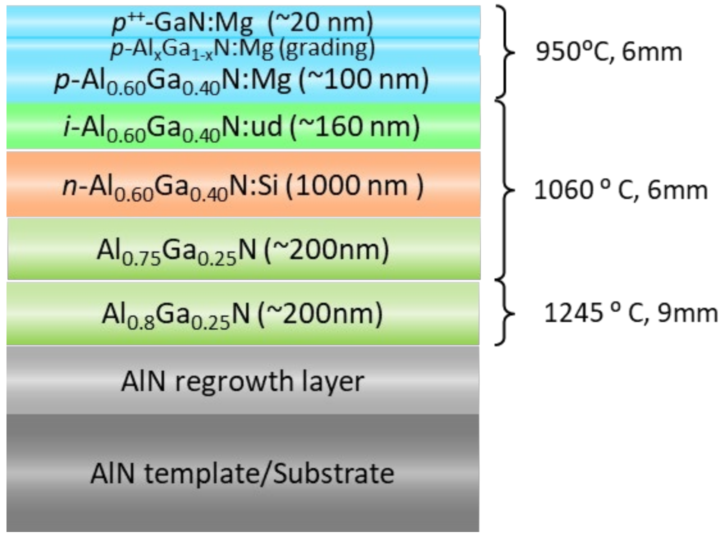


Figure 4: An initial *p-i-n* $Al_{0.60}Ga_{0.40}N$ APD structure for MOCVD process optimization in high-temperature 3x2" MOCVD system. Numbers shown on the right of the structure indicating sample surface temperature and preferred showerhead gap.

	AlN mole fraction	Relaxation %
AlN	0	0
AlGaN1	0.786	9.694329
AlGaN2	0.743	17.7178
AlGaN3	0.597	13.76687
AlGaN4	0.390	8.885027
AlGaN5	0.225	42.06071
AlGaN6	0.070	48.93906

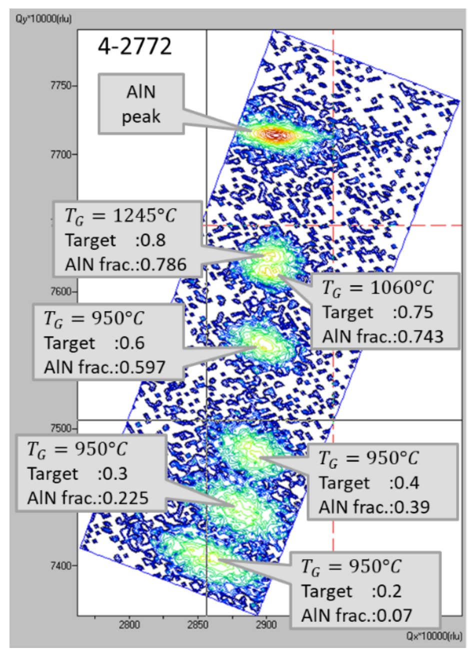


Figure 5: Summary of step-graded AlGaN layers as grown per the structure shown in the previous figure.

For Si doping optimization for the *n*-$Al_{0.60}Ga_{0.40}N$ contact layer, a conventional SiH_4 gas doping source was introduced and the growth was performed under the condition of AlGaN3 (referred to Table in **Figure 3**). As shown in **Figure 6**, free electron concentrations in the range from 2x10^{18} to 1x10^{19} cm^{-3} were achieved with doping efficiency right around 100% as compared to the total supply rate of TMGa and TMAl source. Their resistivity values distribute in the similar range of those of *n*-AlGaN layers previously reported for the AIXTRON 6x2" MOCVD system. Slightly improvement of mobility is also observed.

For *p*-type doping calibration, the experiments were split into 2 parts: (1) growth rate control for the graded AlGaN layer, and (2) Mg doping in the upper *p*-type Mg-doped GaN contact layer. For (1), the growth rate was tuned to match that of $Al_{0.60}Ga_{0.40}N$. An X-ray triple-axis configuration was employed to measure the thickness with only the target AlGaN layer. The thickness was set to be about 50-90 nm while the rest of the AlGaN layers underneath it was set to be below 30nm. A series of samples were grown with a tuned TMGa and TMAl supply rate and characterized until all 4 step-graded AlGaN layers were within 5% of their average growth rate.

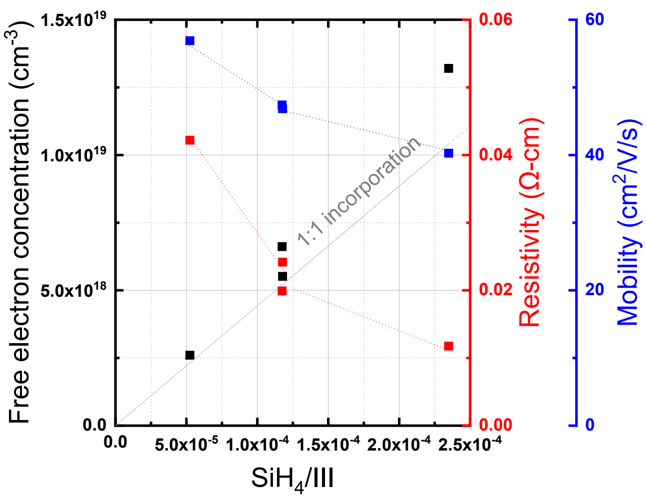


Figure 6: Hall-effect measurement for free-electron concentration, resistivity, and mobility of *n*-$Al_{0.60}Ga_{0.40}N$ as a function of SiH_4/III ratio.

Next, the *p*-GaN layer was grown on a GaN/sapphire template and tuned to match the same growth rate as the step-graded AlGaN layers. After that, a new set of Mg-doped GaN samples were grown and characterized. Comparison of these *p*-GaN:Mg layers with known optimum *p*-GaN and *p*-AlGaN is provided in Table **1** below. However, the resistivity and free-hole concentration of the optimized *p*-GaN in this series are still not as good as the previously obtained system optimum values. Since the *p*-GaN samples in this set, require a higher Mg/III ratio than for previous experiments, it would indicate a possible increase in the compensation of Mg acceptors by background deep-level impurities such as C. We are working on increasing the growth temperature in order to reach the better *p*-type conductivity of the known optimum *p*-GaN:Mg conditions, and reoptimize the Mg doping. Once the value is confirmed, we will have to tune the growth rate of step-graded AlGaN to be used in graded *p*-AlGaN:Mg layer under this new condition before the full device structure can be grown.

Table 1 Optimization summary of Mg doped *p*-GaN grown at 950°C with 6mm gap as highlighted. For comparison, best known optimum *p*-GaN and *p*-$Al_{0.08}Ga_{0.92}N$ samples are included for comparison. The second values of Mg/III in some samples, indicate that such samples emplyed 20nm p^+-GaN contact layer to lower their contact resistance.

Run #	Layer #	Gap	V/III	Mg/III	P_g (*mbar*)	T_g (°C)	Thick. (*nm*)	Bulk concen. ($/cm^3$)	Mobility (cm^2/Vs)	Resistivity (Ω-*cm*)
4-2411-1	*p*-GaN	9	3107	1.58e-2 7.88e-2	100	1060	309.1	8.02E+17	10.0	0.79
4-2523-1	*p*-$Al_{0.08}Ga_{0.92}N$	9	2961	1.5e-2	100	1060	274.4	2.76E+17	9.2	2.45
4-2529-1	*p*-GaN	11	2690 5380	1.42e-2 4.26e-2	100	1010	731.7	9.53e+17	7.8	0.84
4-2783-1	*p*-GaN	6	5724	2.04e-2	100	950	255.7	Negative value		
4-2784-1	*p*-GaN	6	5724	4.08e-2	100	950	253.1	1.358E+17	7.284	6.310
4-2785-1	*p*-GaN	6	5724	6.13e-2	100	950	254.2	2.000E+17	6.318	4.94
4-2786-1	*p*-GaN	6	5724	8.17e-2	100	950	257.8	2.924E+17	6.528	3.27

2. GaN PIN APD Materials Growth and Characterization

As a step in our UV APD device development, GaN-based PIN UV APD devices with various mesa sizes and ohmic contact patterns have been designed to evaluate individual APDs and 6 x 6 APD array performance. A typical epitaxial structure used for these experiments is shown below in Error! Reference source not found..

Table 2 Typical epitaxial layer structure for GaN-based PIN UV APD.

No.		*Layer*	*Material*	*Type*	*Dopant*	*Free-Carrier/Doping Concentration* (cm^{-3})	*Thickness* (nm)
1		*p*-contact	GaN	*p*+	Mg	[Mg] = $1x10^{20}$	20
2		*p*-layer	GaN	*p*	Mg	$p = 1x10^{18}$	100
3		*i*-layer	GaN	*i*	UID	$n < 1x10^{16}$	200
4		*n*-layer	GaN	*n*	Si	$n = 5x10^{18}$	1,000
5		buffer	GaN	*n*	Si	$n = 7x10^{18}$	200
		Substrate	GaN	n^+	Si	$n = 1x10^{19}$	430,000

The epitaxial layers are typically grown on multiple types of GaN-based substrates. In a recent study, in order to compare the performance of APDs grown on GaN substrates having different quality, we grew this GaN PIN APD structure on various bulk, free-standing, and GaN/sapphire substrates. In this specific case, Wafer 2-4610-X with the "X" being 1-6: (-1) a ~3cm x 3cm bulk GaN *n*-type substrate; (-2) an Ammono 25mm dia. bulk GaN *n*-type substrate; (-3) a 50mm dia. MOCVD-grown *n*-type GaN/(0001) sapphire template substrate; (-4) an 1x1cm^2 free-standing GaN *n*-type substrate from Sumitomo Electric; (-5) ¼ of a 50mm dia. free-standing GaN *n*-type substrate grown by Hitachi Cable; (-6) a 50mm dia. GaN/(0001) sapphire substrate.

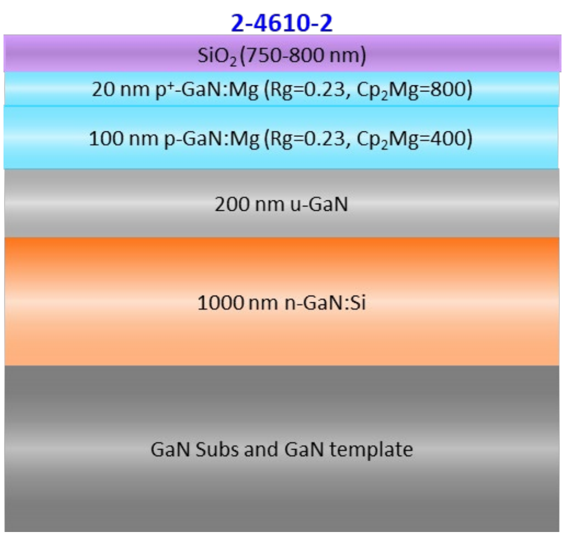


Figure 7: Schematic diagram of the GaN PIN UV APD epitaxial layer structure of Wafer 2-4610-2 grown on a (0001) bulk GaN *n*-type substrate.

The devices from wafer 2-4610-2 have been fabricated into both individual APDs with different optically active areas and also in 6 x 6 arrays of 60 x 60 μm^2 APDs. A schematic diagram of the layer structure is shown in **Figure 7.** In this case, the APD wafer 2-4610-2 structure was grown on an Ammono bulk (0001) GaN *n*-type substrate.

The SIMS data for one of these wafers (2-4610-1) is shown in Error! Reference source not found.. The *p*-layer shows [Mg] ~ $1x10^{19}$ cm^{-3}; the *i*-layer has an intentional Si doping of [Si] ~$1.6x10^{16}$ cm^{-3}; the *n*-layer has [Si] = $6.1x10^{18}$ cm^{-3}. The [O] in the epitaxial layer is [O] ~ $1.3x10^{16}$ cm^{-3} but the [O] in this GaN substrate is high due to the growth process employed for this bulk GaN substrate.

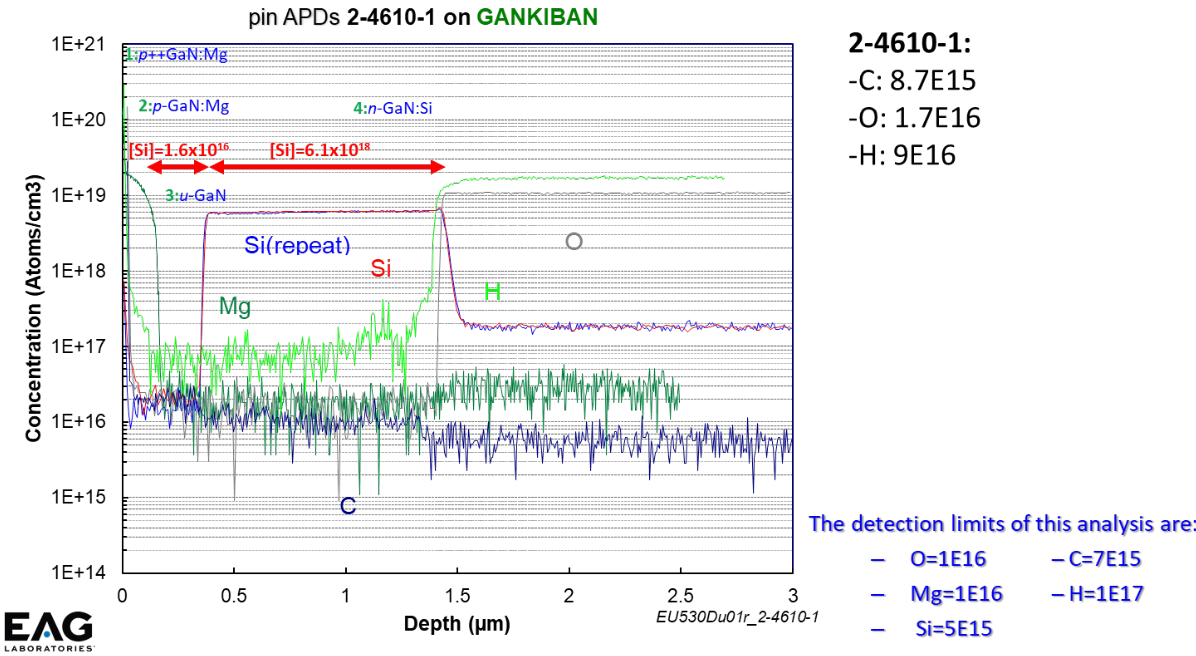


Figure 8: SIMS analysis of GaN PIN APD Wafer 2-4610-1 grown on a FS-GaN substrate.

3. *APD Device Fabrication and Characterization*

As discussed in our last report, in our past work on III-N APDs, we used inductively coupled plasma (ICP) dry etching using BCl_3 or Cl_2 plasmas to create the mesa-geometry individual III-N APD devices in both the singular and array format. These devices were subsequently passivated with a layer of e-beam deposited SiO_2. The ICP process creates inherent plasma damage to the mesa side walls and we have removed this damage using wet chemical etching and SiO_2 passivation. This APD mesa process technology has worked well but requires extra steps and can also result in the introduction of some additional leakage current paths and nonuniformities in performance from device to device. To improve the device performance and yield of APD arrays, we have developed a N-ion-implantation device isolation step to create locally resistive regions as an alternative method to develop a low-leakage APD device area definition to replace the ICP steps. We are using the device processing technology we have previously developed for GaN high-voltage vertical *p-i-n* rectifier devices for fabrication of advanced Geiger-mode UV-APDs.

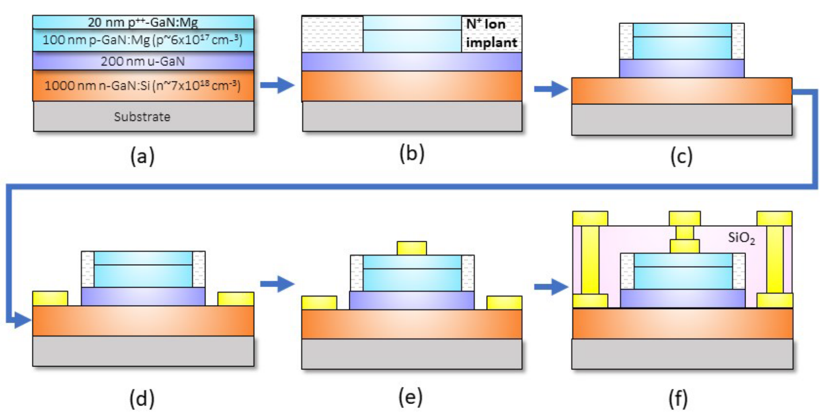


Figure 9: A schematic fabrication processing flow of GaN PIN APDS using nitrogen implantation isolation technique developed at the Georgia Tech.

Shown in **Figure 9** is a GaN APD fabrication processing flow with the inclusion of the nitrogen-ion-implantation isolation technique.

The fabrication starts with a nitrogen-ion implantation that creates a highly resistive region in the as-grown *p*-type GaN layer (**Figure 9** (b)). The implanted nitrogen ions have a dosage of 10^{14} cm^{-2} at an implantation energy of 40 keV. From the SRIM simulation program (The Stopping and Range of Ions in Matter, www.srim.org/), the nitrogen-ion implantation helps create nitrogen vacancies. The nitrogen vacancies create carrier compensation centers in the *p*-type GaN layer. As a result, the *p*-type GaN layer can be converted into a semi-insulating layer. The semi-insulating layer has a sheet resistance of > 100 GΩ/square from our prior study. The depth of the implantation was chosen so that the implantation tail extends no greater than the thickness of the *p*-GaN layer to avoid undesired defect creation due to the ion implantation. The simulated implantation profile shows a longitudinal range of 61.7 nm and a straggle of 27.6 nm with a lateral project range of 26.1nm and a straggle of 32.5 nm at an implantation energy of 40 keV for nitrogen ion implanted into GaN. After the ion-implantation step, the ICP mesa etching is employed with an extension of 5 to 10 microns from the edge of the active device area defined by the implantation isolation (**Figure 9** (c)). The fabrication processing then proceeds with the previously established processing steps that were developed earlier, namely, the *n*-contact metallization, the *p*-contact metallization, the device passivation using spin-on-glass, accessing via holes, and device interconnects, respectively (**Figure 9** (d) – (f).)

The ion-implantation isolation is effective in suppressing the sidewall leakage current component. As shown in **Figure 10**, the low-voltage leakage current was suppressed to below 2 fA (below the instrument's detection floor for the Keithley 4200-SCS semiconductor parameter analyzer used in these measurements) in the nitrogen-ion implanted APDs for the applied reverse biases of -5 to -30 V. The extracted noise equivalent power (NEP) was < 6.3 x 10^{17} W-$Hz^{-0.5}$ at a reverse bias voltage of 20 V. This result showed an extended low-leakage current range compared to our previously reported GaN PDs with similar PIN structure[1].

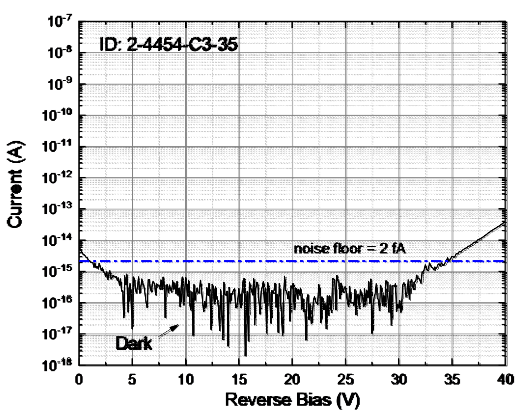


Figure 10: A leakage current measurement for an APD showing an ultralow device leakage current below the detection limit of the instrument between -5 to -30V. (Wafer ID: 2-4454-2)

The wafers were processed into individual APDs having various active areas and 6 x 6 element device arrays having 60 x 60 μm^2 pixels using low-damage inductively coupled plasma (ICP) etching and N-ion implantation for device isolation. Shown in **Figure 12** is an optical photograph of two typical types of the many individual APD device designs. The dotted circled area is where the optically active region is located. The device electrically active area is established by the definition of the N-ion implanted region that creates a high-resistive region. The ICP-etched mesa is a larger diameter region that allows access to the *n*-type layer in the device structure.

Several different blocks of GaN PIN APD devices were tested from Wafer 2-5554-2 described above. The reverse-bias *I-V* characteristics of nine sequential devices measured from one block

[1] Zhang, *et. al., Applied Physics Letters* 94, 221109 (2009).

are shown in **Figure 11**. These data show the good uniformity of these device characteristics. Further studies of the UV photoresponse of these devices is currently underway.

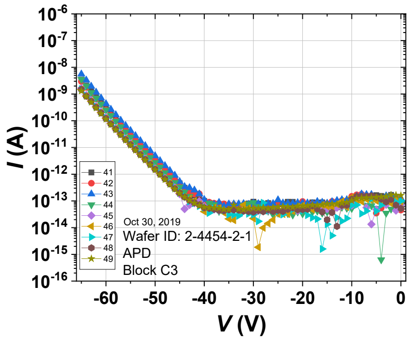


Figure 11: Reverse-bias *I-V* characteristics of nine sequential APDs from Block C3 of Wafer 204454-2.

Our work in this APD array process development was interrupted by the COVID-related shut down. We are now continuing the preliminary characterization of the first ion-implanted 6x6 APD arrays. The reverse-biased *I-V* characteristics of the individual ion-implanted GaN APDs under dark conditions were evaluated prior to device completion for process control as shown for a typical device in **Figure 13** up to the reverse bias of V_R = -70 V from wafer 2-4610-2 (grown on an ammonothermal bulk GaN substrate). These devices were not fully processed at this stage of testing, so we did not take the device reverse bias out to avalanche breakdown which, in this case, was V_R =-85V. By using N-ion implantation for device isolation, the dark current was much lower than the comparable APDs processed with dry etching, with dark currents below ~10^{-10} A at reverse bias up to -70 V.

To evaluate the uniformity of our GaN APD epitaxial growth and APD device processing, we are in the process of completing the fabrication and testing the dark and illuminated *I-V* (and *J-V*) characteristics of many individual devices having different device areas at different points across the 1.5 x 1.5 cm^2 wafer pieces selected from several wafers grown in the same epitaxial growth run. The *I-V* data from another wafer grown in the same run as the device of **Figure 13** is shown in (Wafer 2-4610-5, grown on a free-standing HVPE-grown GaN substrate). The typical reverse-bias APD *I-V* characteristics up to V_R = -65 V for a set of individual 80 μm dia. APDs are shown in **Figure 16**. As shown, the reverse-bias *I-V* characteristics are quite uniform between different wafers within the measurement system limitations suggesting that the materials and device processing have an excellent degree of uniformity.

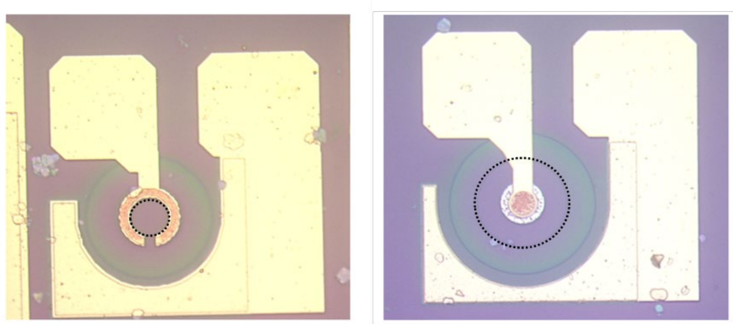


Figure 12: Optical micrograph of two types of single APDs fabricated with *N*-ion implantation.

Studies of the semi-log plots of the forward *I-V* characteristics of a variety of 11 individually fully processed APDs having various APD sizes, ranging from 25 μm to 51 μm in radius fabricated from wafer 2-4610-2, grown on a bulk GaN substrate are shown in **Figure 14**. The reverse semi-log *I-V* characteristics for these same 11 devices are shown in **Figure 15**. These fully processed devices have an excess leakage current compared to the individual APD devices in **Figure 13** fabricated from the same wafer due to a process step that used spin-on-glass (SoG) for passivation and this SoG was out of specification and we believe this led to an excess leakage current near zero bias. However, these data show a very good uniformity for both forward- and reverse-bias *I-V* characteristics.

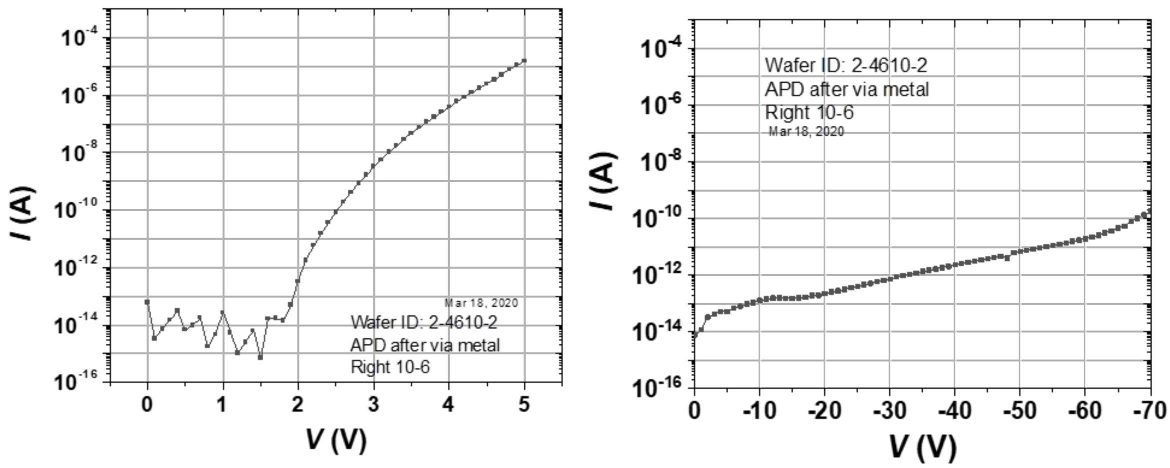


Figure 13: Forward and reverse-bias semi-log *I-V* characteristics of an individual ion-implanted 82 μ*m*-dia. GaN APD from Wafer 2-4610-2 (Device 2-4610-2_S2_J6). This substrate is an ammonothermal bulk GaN substrate.

An SEM photograph of an area of one of the processed wafers with 6 x 6 APD arrays is shown in **Figure 17**. An optical microscope image of a region of one of these complete arrays is shown in **Figure 18** These arrays have two basic designs, one has square APD elements and the other (not shown) have circular APD elements. These APDs have an SiO_2 layer as a top passivation layer. These devices are currently being tested for *I-V* characteristics and photoresponse over the range 220nm < λ < 400nm.

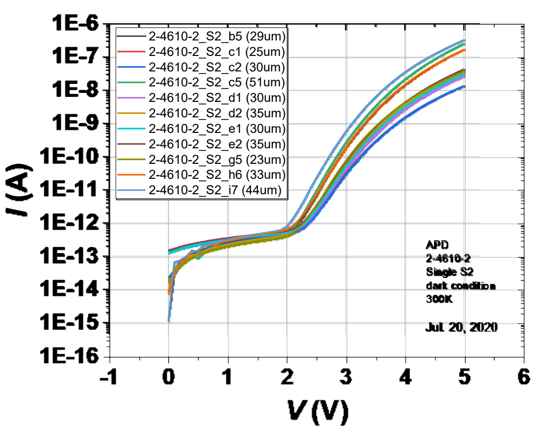


Figure 14: Log forward *I-V* characteristics of GaN PIN APDs from wafer 2-4610-2 with various radius values.

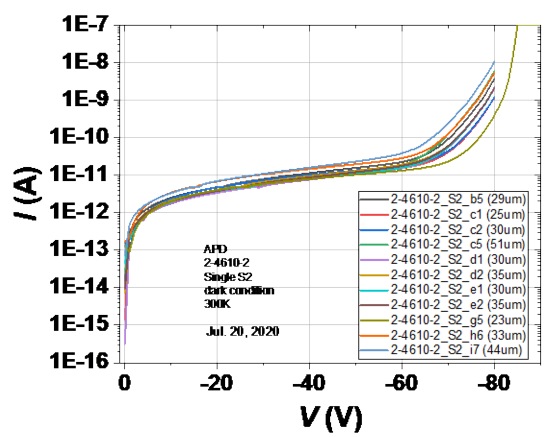


Figure 15: Log reverse *I-V* characteristics of GaN PIN APDs from wafer 2-4610-2 with various radius values.

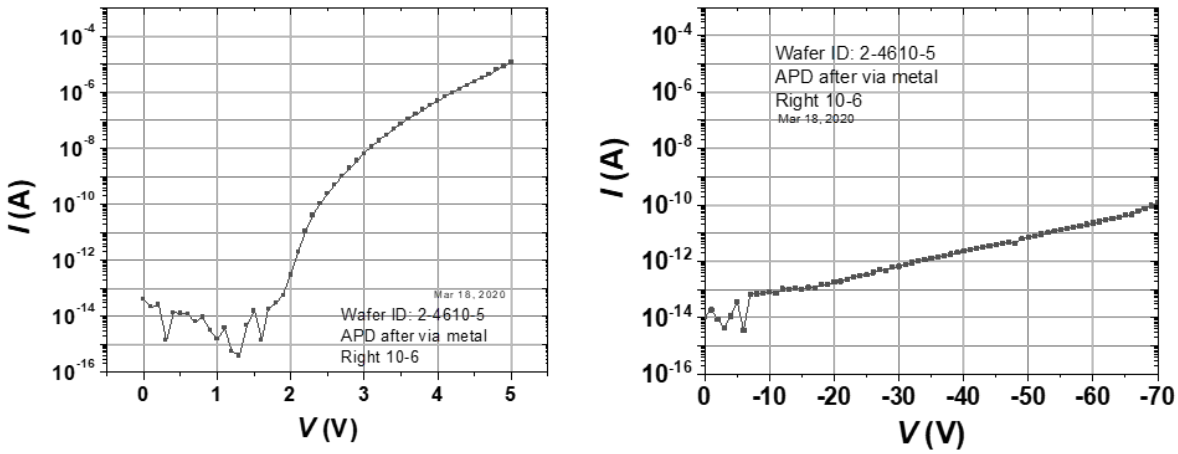
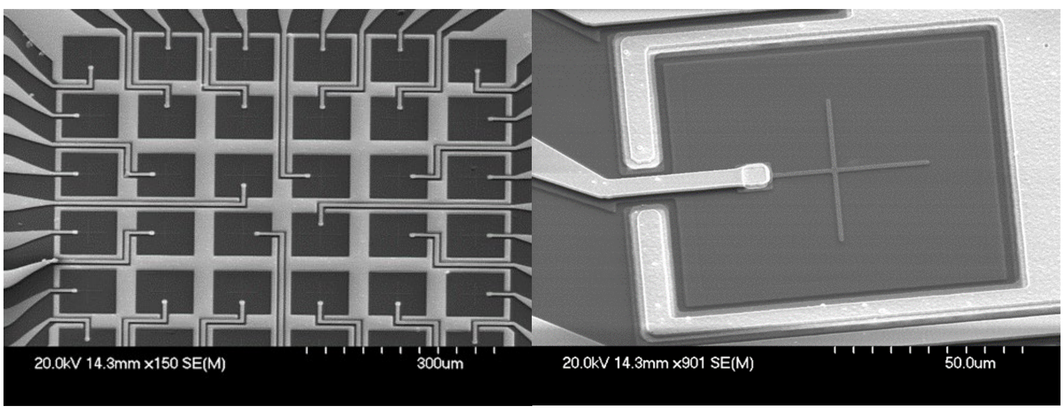


Figure 16: Forward and reverse-bias *I-V* characteristics of an individual ion-implanted 82 μ*m*-dia. GaN APD from Wafer 2-4610-5 (Device 2-4610-5_S2_J6). This substrate is a free-standing GaN *n*-type substrate.



(a) (b)

Figure 17: (a) SEM photograph of a portion of a 6 x 6 array of square 60 x 60 μm^2 ion-implanted APDs; (b) SEM photograph of one of the pixels in this array.

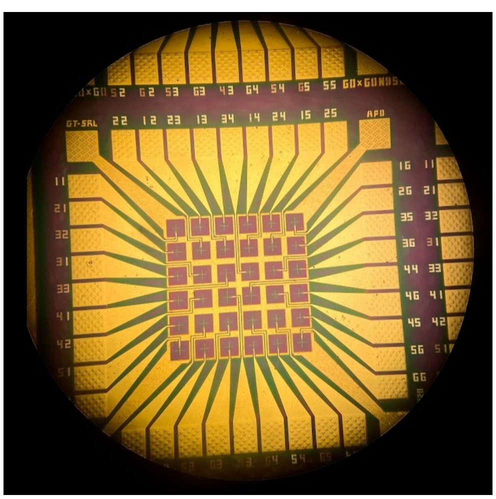


Figure 18: Optical microscope image of 6x6 GaN PIN square ion-implanted APD array. Individual APD size is 65 μm x 65 μm.

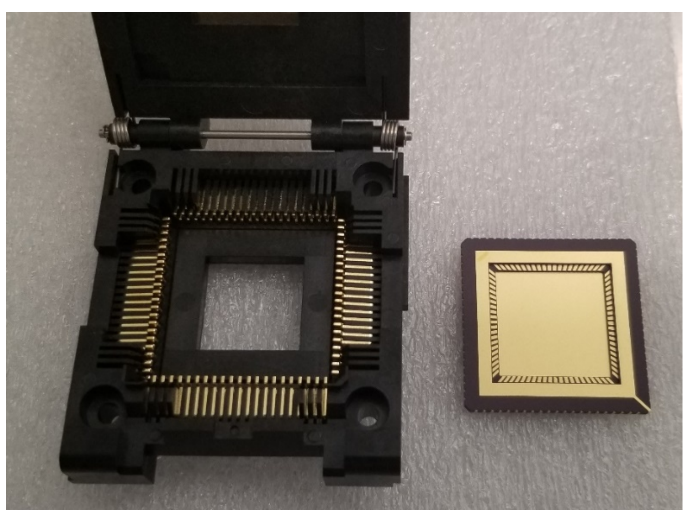


Figure 19: Image of the GaN APD array chip carrier that will be used in this program.

4. Geiger-Mode Testing of GaN UV PIN APDs

The use of low-defect density GaN substrates is a critical element to realizing high-performance GaN/AlGaN single-photon detection (Geiger-mode. GM) UV-APDs and arrays for the suppression of dark current and jitter under high electric fields, as well as for enabling large UV-APD pixel size and APD arrays with uniform device performance. The GaN-based PIN APD devices have been designed and characterized with the goal of enhancing the quantum efficiency, significantly reducing the dark current and noise multiplication near the avalanche breakdown voltage and demonstrating high-performance Geiger-mode APD operation at and around 355 nm. These approaches are leading to extremely low leakage currents in the reverse bias range near avalanche breakdown, a necessary requirement for stable Geiger-mode operation for single-photon counting. Single-photon operation of the GaN-based front-illuminated individual UV-APD arrays can improve low illumination device detection and imaging performance for high sensitivity applications.

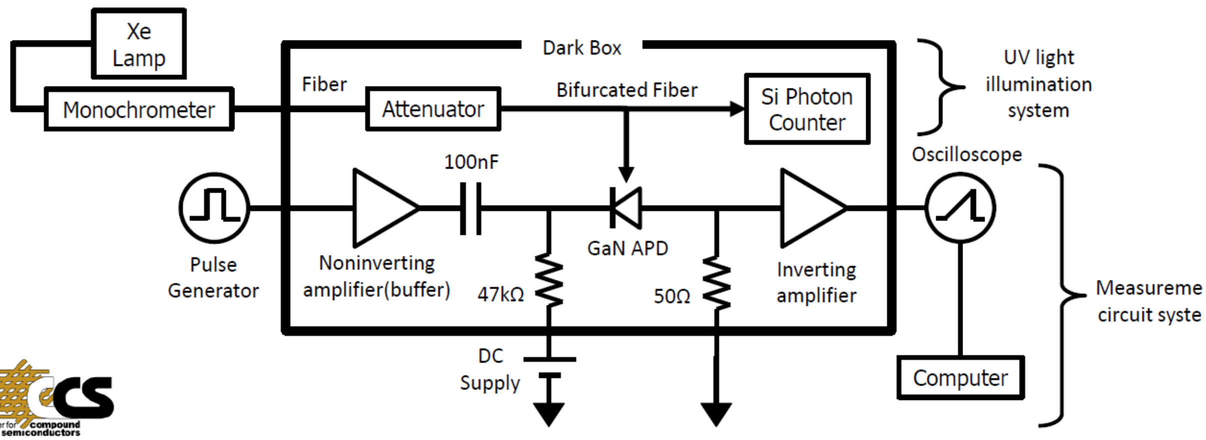


Figure 20: Schematic diagram of Geiger-mode testing setup, consisting of a UV illumination system and measurement circuit system.

A device testing system was created to measure the GM performance of our top-illuminated GaN PIN APDs consisting of a measurement circuit system and UV-illumination system, as shown schematically in **Figure 20**. In the measurement circuit system, a rectangular pulse is created from a pulse generator. A noninverting amplifier (buffer) is inserted after the pulse generator to isolate the pulse generator from the rest of the circuit. The oscilloscope measures the avalanche current by measuring the voltage across a 50 Ω resistor, which is connected after the GaN UV-APD. An inverting amplifier is inserted between the GaN UV-APD and an oscilloscope to prevent RF signal reflection. Finally, a computer connected with the oscilloscope collects a series of avalanche signals and performs data processing. The circuit elements including amplifiers, resistors, capacitors, and the GaN UV-APDs are kept inside a dark box.

In the UV illumination system set up for single-photon detection efficiency (SPDE) measurements, a broad spectrum of UV light from a Xenon lamp (Osram XBO 150W/4) is sent to a monochromator (Newport 74100 / Cornerstone 260) to select the narrow band of wavelengths. The selected wavelength of light is attenuated by an attenuator and split by a bifurcated fiber. One end of the bifurcated fiber is directed to a Si photon counter module for reference, and the other end of the fiber is directed to the GaN UV-APD under test. The attenuator, the bifurcated fiber, and the Si photon counter module are likewise placed inside the dark box, which was tested with the Si photon counter for light leakage.

The principle of measurement of the Geiger-mode operation of the APD is based on Poisson statistics. First, when the pulse is "off" (0 V), only a DC bias voltage below avalanche breakdown is applied across the GaN UV-APD. When the pulse is "on" (8 V), the rectangular pulse triggers avalanche breakdown. The rising edge of the pulse does not immediately trigger an avalanche current in the GaN UV-APD, but it takes some time within the pulse to trigger an avalanche current. As shown in Figure 6, the avalanche current keeps its level until the falling edge of the input pulse when the GaN UV-APD is quenched. With the count rate obtained from histogram fitting, it is possible to use the following relationship to obtain the photon detection efficiency (PDE) of the GaN APD, since the PDE of the Si photon counter is already known:

$$\frac{R_{P+D,Si}-R_{D,Si}}{R_{P+D,GaN}-R_{D,GaN}} = \frac{PDE_{Si}}{PDE_{GaN}} \qquad (1)$$

In Eq. (1), $RP+D,Si$ is the dark + photon count rate of the Si photon-counter module, RD,Si is the dark-count rate of the Si photon-counter module, $RP+D,GaN$ is the dark + photon count rate of the GaN APD, RD,GaN is the dark count rate of the GaN APD, $PDESi$ is photon detection efficiency of the Si photon counter module, and $PDEGaN$ is the PDE of the GaN UV-APD. Now that a procedure is in place for characterizing the PDE of the UV-APD detectors, the goal looking forward is to achieve and verify through measurement high PDEs (e.g., above 20%) from UV-APD devices at ~350- 365 nm. Such enhancements in detector sensitivity can help advance the technology and its adaption for UV detection applications.

We are planning to make temperature-dependent measurements of the GM APD operation and have designed a temperature-controlled testing system for these measurements. Shown in **Figure 21** is a blow-up diagram of the major elements in this system. **Figure 22** shows the fabricated module and the optical system developed for directing the UV light to the top of the individual APDs.

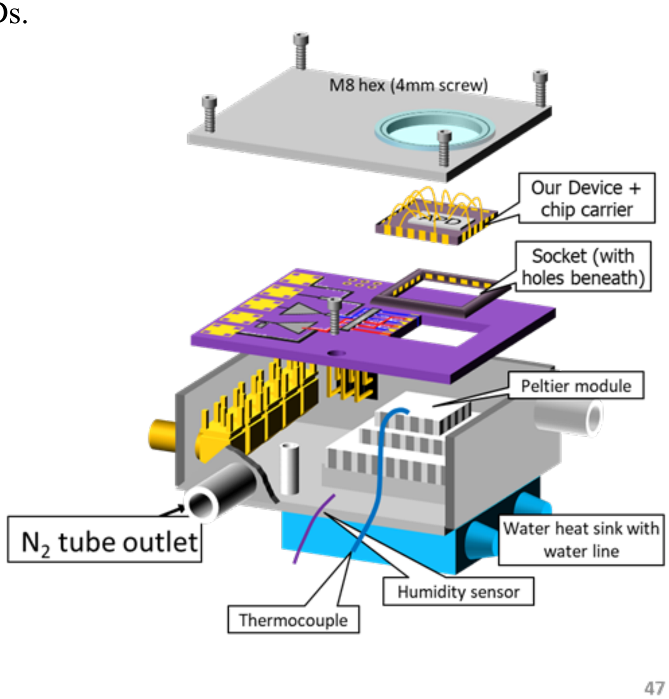


Figure 21: Schematic diagram of temperature-variable GM APD measurement system.

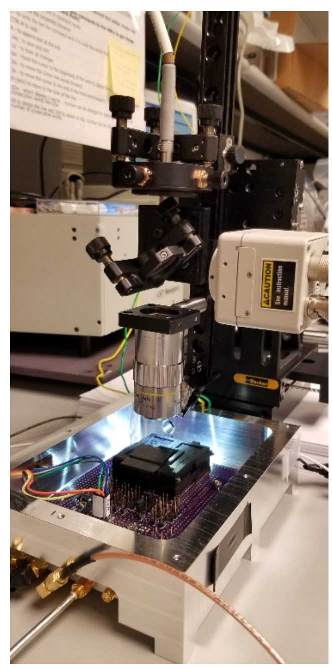


Figure 22: Photograph of the UV illumination system for GM testing.

5. Future Research

Future research in this area will continue the testing and development of these GaN-based and AlGaN-based GM APD arrays for advanced imaging applications. We will continue to develop larger arrays of APDs and study the performance uniformity achievable. We will also develop "window-layer" GaN APDs with AlGaN *p*-type window layers to improve the overall near-UV photoresponse for GaN-based GM-APD arrays. Our first application target for the GaN-based APD arrays is for λ = 355nm LIDAR applications.

Another future activity is to develop back-side illuminated GaN-based APD arrays using back-side via-holes centered on each pixel. This can be done by wafer thinning and localized selective etching or by substrate removal using a selectively etched InGaN "zipper layer".

Related Conference Presentations During the Period Aug. 2019 – Aug. 2020

1. A. K. Sood, J. W. Zeller, P. Ghuman, S. Babu, N. K. Dhar, A. W. Ghosh, and R. D. Dupuis, "Development of high-performance detector technology for UV and IR applications," *Proc. SPIE* Vol. 22251, p. 1115113 (11 p.) (2019).
2. Minkyu Cho, Hoon Jeong, Chuan-Wei Tsou, Marzieh Bakhtiary-Noodeh, Theeradetch Detchprohm, Russell D. Dupuis, and Shyh-Chiang Shen, "Low-Noise GaN *p-i-n* Avalanche Photodiodes for Ultraviolet Applications Using an Ion-Implantation Isolation Technique," Conference on Lasers and Electro-Optics (CLEO) 2020, Virtual conference, May 11-15, 2020.
3. Marzieh Bakhtiary-Noodeh, Minkyu Cho, Chuan-Wei Tsou, Hoon Jeong, Shyh-Chiang Shen, Theeradetch Detchprohm, Ashok K. Sood, and Russell D. Dupuis, "Homojunction GaN *p-i-n* Ultraviolet Avalanche Photodiodes Using Ion-Implantation Isolation," *62nd Electronic Materials Conference (EMC 2020),* Virtual conference, June 24-26, 2020.
4. Hoon Jeong, Eliza A. Gazda, Mi-Hee Ji, Minkyu Cho, Marzieh Bakhtiary-Noodeh Theeradetch Detchprohm, Shyh-Chiang Shen, A. Nepomuk Otte, and Russell D. Dupuis, "Geiger-mode Operation of Gallium Nitride p-i-n Avalanche Photodiodes and Histogram Fitting Measurement," *62nd Electronic Materials Conference (EMC 2020),* Virtual conference, June 24-26, 2020.

Related Publications During the Period Aug. 2019 – Aug. 2020

1. A. Sood, J. W. Zeller, P. Ghuman, S. Babu, and R. D. Dupuis "GaN/AlGaN avalanche photodiode detector technology for high performance ultraviolet sensing applications," *Proc. SPIE* 11530, 115300Q (2020). https://doi.org/10.1117/12.2573387.

Training Opportunities

During the course of this program, eight Georgia Tech PhD graduate students and five Post Docs in the School of ECE worked on this project. This includes one female ECE PhD student who graduated and then worked as a Post Doc in Dupuis' group and is now a Post Doc at Oak Ridge National Labs and will soon move to a permanent research staff position at the US Army Research Laboratory in Adelphi MD. In addition, two of the current PhD students currently working on this project are female, one in ECE and one in Materials Science and Engineering.