REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 23-08-2023	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Mar-2019 - 29-Feb-2020

4. TITLE AND SUBTITLE Final Report: DURIP: Semiautomated Optoelectronics Characterization System for Deep-Ultraviolet Photodetectors and Solar Cells	5a. CONTRACT NUMBER W911NF-19-1-0130
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611103
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of California - Davis Sponsored Programs 1850 Research Park Drive, Suite 300 Davis, CA 95618 -6153	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 73803-ES-RIP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

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			Jerry Woodall
UU	UU	UU	UU		19b. TELEPHONE NUMBER 530-752-9581

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 24-Aug-2023

Agency Code: 21XD

Proposal Number: 73803ESRIP **Agreement Number: W911NF-19-1-0130**

INVESTIGATOR(S):

Name: Jerry M. Woodall
Email: jwoodall@ucdavis.edu
Phone Number: 5307529581
Principal: Y

Organization: **University of California - Davis**
Address: Sponsored Programs, Davis, CA 956186153
Country: USA
DUNS Number: 047120084 EIN: 946036494
Report Date: 31-May-2020 Date Received: 23-Aug-2023
Final Report for Period Beginning 01-Mar-2019 and Ending 29-Feb-2020
Title: DURIP: Semiautomated Optoelectronics Characterization System for Deep-Ultraviolet Photodetectors and Solar Cells
Begin Performance Period: 01-Mar-2019 **End Performance Period:** 29-Feb-2020
Report Term: 0-Other
Submitted By: Jerry Woodall Email: jwoodall@ucdavis.edu
Phone: (530) 752-9581
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 1 **STEM Participants:** 2

Major Goals: see final report

Accomplishments: The major activities were students and faculty successfully using the equipment awarded under the DURIP contract to broaden the scope of resulting publications in the open literature and theses.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Ryan James Bunk
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

RPPR Final Report
as of 24-Aug-2023

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Jerry M. Woodall
Signature Date: 8/23/23 6:52PM

DURIP: Semiautomated Optoelectronics Characterization System for Deep-Ultraviolet Photodetectors and Solar Cells

AWARD: W911NF1910130

Final Report

Introduction:

It is well known that wide band gap semiconductor materials and devices are becoming an ever-increasing component in both electronic and photonic device applications. In order to understand the importance of this DURIP being awarded to UCD, a brief summary of the origin of early photonic device breakthroughs based in wide-gap semiconductors is useful. For this discussion, we arbitrarily define wide-gap materials as those with band gaps > 2.2 eV, e.g., just below the band gap of GaP.

The wide-gap photonic device “movement” had a “false start” with the achievement of room temperature, cw, green lasers, made with heterojunctions of ZnSe (BG = 2.7 eV). This breakthrough resulted from a previous breakthrough of being able to p-dope ZnSe. However, stimulated emission in the lasing region of ZnSe laser diodes caused rapid degradation of the laser. As a result, interest in the ZnSe laser breakthrough was short lived. Since prior to the p-doped ZnSe breakthrough, most II-VI textbooks taught that achieving p-doping in wide-gap semiconductors would be problematic, owing to the equilibrium doping compensation physics, which can limit p-doping of wide-gap materials. Thus, in itself, the achievement of p-doped ZnSe result inspired renewed interest in the possibility in achieving p-n junctions in other wide-gap materials.

Wide-gap materials and device research escalated when Shuji Nakamura fabricated high efficiency blue emitting LEDs using double heterojunctions of GaN/InGaN/GaN. After that, GaN produced blue and UV lasers. This breakthrough, as for the ZnSe laser, happened when Nakamura and his colleagues figured out how to dope GaN p-type. As a result of fabricating efficient blue-UV GaN LEDs, they became the LED optical driver of the of the now commercially ubiquitous white LEDs. As a result, Nakamura and colleagues shared the 2014 Nobel Prize in physics. And when GaN based high frequency power devices were fabricated, GaN became most widely used compound semiconductor material for commercial semiconductor devices, even eclipsing GaAs as the preferred compound material of choice for devices.

Current Wide-gap Research:

The current interest in wide-gap research is focused on two major applications, power electronics and UV photonics. Power electronics application are mostly focused on devices that will operate at high reverse breakdown voltages and low forward-biased resistance. The UV photonic devices have applications that include UV-solar blind detectors and toxic chemical detection.

High Voltage Power Devices.

As is well known powering vehicles with electricity rather than fossil fuels has the advantage of lowering the carbon footprint, which, in turn, offers the possibility of stabilizing global warming. Thus, there is a global effort to replace fossil fuel powered vehicles with electricity powered vehicles (EVs) using Li based batteries and electric motors. The technical problem is that batteries supply DC current whereas electric motors operate most efficiently when the electro-magnets are driven with AC current. This restraint requires the use of inverters which convert DC current to AC current. Since, e.g., a Model 3 Tesla operates at a max output power

>200kW, both the inverters and the motor controllers ideally need to operate a high voltages and modest currents (low forward-bias resistance).

Fortunately, the power device community has develop figures-of-merit (FOM) which relate band gap energies (Eg) to operational parameters for semiconductor-based power electronics. For example, the Baliga FOM is proportional to Eg cubed. Even though GaN (Eg = 3.4 eV) and SiC (Eg = 3.26 eV) have FOM much higher than those of Si (Eg = 1.12 eV) and GaAs (Eg = 1.42 eV), both of these materials suffer from device fabrication issues. GaN cannot easily be formed into defect free GaN substrates upon which low cost, large area, defect free GaN epitaxy, which high voltage power devices require. SiC can be formed into large area substrate, but the cost is nearly 100x that for large area Si substrates with no viable cost reduction laboratory scale technology available. Nonetheless, SiC is the current material of choice for the next generation of inverter devices.

The arrival Ga_2O_3 (GOX)

Near the beginning of the second decade of the 21st century there was a resurgent interest in GOX. Since its Eg is 4.7-4.8 eV, it has a very high Baliga FOM. As a result, it has become a material of interest for power electronics. The good news is that GOX substrates can be grown by the Czochralski method like that used for Si. However, GOX has two important limitations with respect to its use as a wide-gap semiconductor for next generation high voltage EV applications.

First, it has a low thermal conductivity <0.1 times that for GaN and SiC. Since having a high thermal conductivity is important for high voltage power device heat extraction, GOX device will need to be thin and bonded to a high thermal conductivity substrate. Another limiting feature is that GOX lacks a valence band structure that can produce hole conductivity. This property precludes making any type of bipolar device, including p-n junction diodes and bipolar junction transistors, thus likely limiting GOX to MOSFET type transistors. In spite of these limitations, there is much current R&D being pursued internationally on: 1) improving the preparation of high quality large diameter GOX bulk crystals per se, and, as substrates for GOX epilayer deposition; 2) investigating the fundamental solid-state physics of GOX; 3) a search for sensible device applications, especially for its use for high voltage power electronics.

Studying GOX and Other Wide-gap Semiconductors at UCD with the DURIP Award:

When this DURIP was proposed and awarded, there were three UCD-ECE faculty who had an immediate interest in using its capabilities. These were Profs. J.M. Woodall, Saif Islam, and Srabanti Chowdhury.

Prof. Woodall's research program had two wide-gap semiconductors projects which had successful conclusions, owing in part to the DURIP award. Ryan J. Bunk, an M.S. degree candidate under Woodall's supervision, headed a project that explored the optical properties of GOX, which resulted in a successful UCD-ECE M.S thesis titled, "Design and Implementation of Ga_2O_3 Deep-UV Photodetectors with Improved Intrinsic Solar Band Rejection" (1). Bunk studied a variety of GOX devices from external colleagues including those he had fabricated and those supplied by Prof. Islam's students. Bunk employed the DURIP equipment to assess the UV optical properties of the GOX samples. The conclusion of his thesis was that while some samples showed improved solar band rejection, the improvement was not sufficient enough to exceed the commercial specifications of UV-solar blind, Si high pass photodetectors, or the improved solar band rejection over some of those in the open literature.

Hui-Ying Sao, a Ph.D. degree candidate under Woodall's supervision, explored epilayer fabrication techniques aimed at improving the short wavelength response of GaP based solar cells. Using the liquid phase epitaxy method of epilayer growth, she fabricated GaP p-n junction solar cells with significantly improved spectral response, not just for short wavelengths, which indicated reduced surface recombination loss, but for ***over the entire spectral range, < 525 nm, for which GaP can generate minority carriers and produce output current.*** Thus, the response data showed both lower surface state density and lower trap density in the bulk of the GaP solar cell. She also, employed the DURIP equipment to measure the cells response to UV wavelengths (2).

Prof. Islam's former Ph.D. candidate student, Badriyah Alhalaili, studied the UV detection properties of GOX nanowires using the DURIP equipment, which resulted in the widely referenced paper, "Gallium oxide for UV detection with enhanced growth and material properties" (3). The theoretical motivation for this work was that nano-needles have a higher surface area to volume ratio and, hence, would offer higher photo carrier collection efficiencies compared to planar films. This was investigated and confirmed experimentally. Further enhancement to detectivity was associated with the presence of intentionally introduced nano particles of Ag.

Prof. Chowdhury, during her career at UCD-ECE, had a large research program with numerous students exploring the development of GaN based high-voltage power devices. Most of here students were known to use the DURIP equipment to characterize the GaN epilayer films used for their power device projects.

Summary and Assessment:

In summary, it is the view of the PI that the availability of the DURIP equipment at UCD resulted in a very positive impact of the work product that resulted from its use.

Respectfully submitted,

Jerry M. Woodall
Professor of Electrical and Computer Engineering
University of California at Davis.

References:

1.Ryan James Bunk, "Design and Implementation of Ga_2O_3 Deep-UV Photodetectors with Improved Intrinsic Solar Band Rejection", UCD MS Thesis (2020).

2. Hui-Ying Siao, Ryan J. Bunk, and Jerry M. Woodall, "Gallium Phosphide Solar Cell Structures with Improved Quantum Efficiencies", Journal of ELECTRONIC MATERIALS, Vol. 49, No. 6, (2020) https://doi.org/10.1007/s11664-019-07848-6.

3. Badriyah Alhalaili, Ryan James Bunk, Howard Mao, Hilal Cansizoglu, Ruxandra Vidu, Jerry Woodall and M. Saif Islam, "Gallium oxide for UV detection with enhanced growth and material properties", ***Scientific Reports***, (2020) 10:21434.