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

DTRA-TR-16-24

TECHNICAL REPORT

Design of Semiconductor Heterostructures for Suppression of Electronic Processes Caused by Radiation-Induced Defects

Distribution Statement A. Approved for public release; distribution is unlimited.

March 2019

HDTRA1-11-1-0052

Gary W. Wicks

Prepared by:
University of Rochester
518 Hylan Building
Rochester, NY 14627

DESTRUCTION NOTICE:

Destroy this report when it is no longer needed.
Do not return to sender.

PLEASE NOTIFY THE DEFENSE THREAT REDUCTION AGENCY, ATTN: DTRIAC/ RD-NTF, 8725 JOHN J. KINGMAN ROAD, MS-6201, FT BELVOIR, VA 22060-6201, IF YOUR ADDRESS IS INCORRECT, IF YOU WISH IT DELETED FROM THE DISTRIBUTION LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
00/03/2019

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
07-13-2011 - 07-17-2014

4. TITLE AND SUBTITLE
Design of Semiconductor Heterostructures for Suppression of Electronic Processes Caused by Radiation-Induced Defects

5a. CONTRACT NUMBER

5b. GRANT NUMBER
HDTRA1-11-1-0052

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Gary W. Wicks

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Rochester
518 Hylan Building
Rochester, NY 14627

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Threat
Defense Threat Reduction Agency
8725 John J. Kingman Road
Fort Belvoir, VA 22060-6201

10. SPONSOR/MONITOR'S ACRONYM(S)
DTRA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DTRA-TR-16-24

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The project analyzes semiconductor infrared (IR) detectors and their performance degradation caused by material defects. Newly developed unipolar barrier detectors were compared, both theoretically and experimentally, with the traditional pn-based detector designs. In cases where defect concentrations are significant, e.g., mismatched epitaxial material or radiation damaged material, unipolar barrier devices exhibit superior performance in terms of the magnitude of the dark current and the efficiency of dark current reduction by cooling.

15. SUBJECT TERMS
infrared detector, dark current, defects, radiation hardness, epitaxy

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jacob Calkins
U	U	U	SAR	8	**19b. TELEPHONE NUMBER** *(Include area code)* 571-616-3075

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

Final Report

DTRA Program HDTRA1-11-1-0052

Design of Semiconductor Heterostructures for Suppression of Electronic Processes Caused by Radiation-Induced Defects

G. Wicks
University of Rochester

July 20, 2015

1. Introduction

The project analyzes semiconductor infrared (IR) detectors and their performance degradation caused by material defects. Other programs have sought to minimize performance degradation by defects through a materials-based approach of seeking semiconductor materials that contain fewer defects or are less prone to defect formation by radiation. This project takes a complementary approach, developing device architectures that are less affected by the presence of defects. The main "defect tolerant" device design investigated is the unipolar barrier infrared detector. This project compares the effects of defects on the dark current of conventional pn-based IR detectors with those based on unipolar barrier. The work in this project involves modeling defect processes in pn and unipolar barrier devices, comparison of experimental measurements with the model, and development of device architectures to suppress defects' effects. Defects are intentionally introduced by using radiation (63 MeV protons) and also by using semiconductor epitaxial materials, which are lattice-mismatched (to their substrates).

2. Results and Discussion

A collaboration was established with the Air Force Research Laboratories (AFRL) at Kirtland AFB (D. Cardimona, C. Morath, V. Cowan). The AFRL group specializes in radiation effects in semiconductor IR detectors and is a natural collaborator in this project as their capabilities are complementary with ours and very relevant to the program. We have examined irradiated test devices through AFRL's irradiation runs at UC Davis Cyclotron using 63 MeV protons. Unipolar barrier infrared detectors, fabricated in InAsSb / AlAsSb epitaxial materials on GaSb substrates have been examined. The experimental findings led to the development of a theoretical model of effects of defects on dark current of IR detectors (both conventional pn-based and the unipolar barrier defect-tolerant design). The objective of the modeling was to theoretically determine defects' effects that are accessible to experimental verification. The modeled dark currents of the unipolar barrier designs were found to have different dependence of defect concentration, depending on the relationship between the minor carrier diffusion length and the thickness of the absorbing layer of the device, as shown in figure 1.

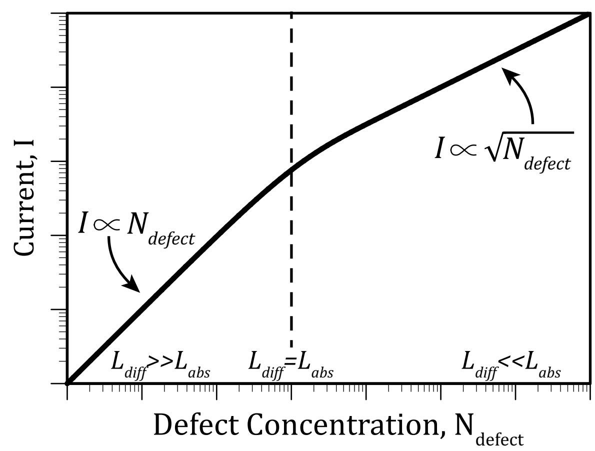

Figure 1: Modeled dark current of unipolar barrier as a function of increasing defect concentration. There are two regimes, depending on the relationship between the minority carrier diffusion length, L_{diff}, and the thickness of the detector's absorber layer, L_{abs}. Under low defect concentrations the detector remains in the long diffusion length limit, but under high defect concentrations the detector enters the short diffusion length limit and the dark current dependence on the defect concentration reduces.

A proton-irradiated unipolar barrier detector was examined, within the context of the above model. The concentration of radiation-induced defects is proportional to

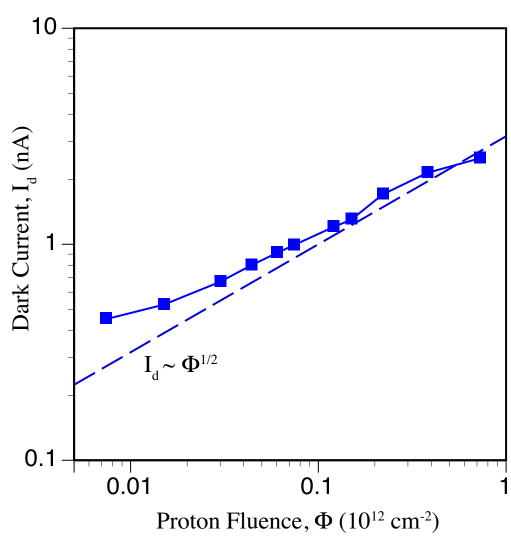

Figure 2: Dark current as a function of proton fluence for an irradiated unipolar barrier detector. The detector exhibits a dark current dependence proportional to the square root of the defect density indicating the short diffusion length limit.

the proton fluence. As shown in figure 2, the device's dark current exhibited a square dependence on proton fluence, and hence also on defect concentration. The model implies that this device was in the short diffusion length regime.

The magnitudes and the temperature-dependence of dark currents of the newly developed unipolar barrier detectors were compared with the traditional pn-based detectors. The model developed in this program indicates that the dark currents of these devices will have different temperature dependences: pn-based detectors' dark currents will exhibit thermal activations of half the bandgap energy, whereas unipolar barrier detectors' dark current thermal activation energies will be the full bandgap energy. Experimental investigation verified the model, as shown in figure 3.

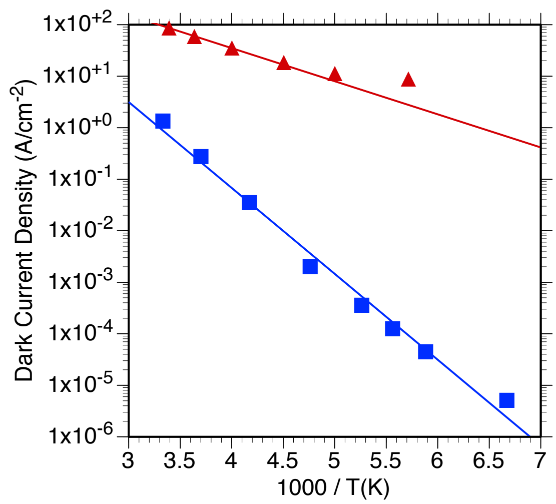

Figure 3: Arrhenius analysis for an InAs unipolar barrier detector (blue) and a conventional photodiode (red) grown on GaAs substrates. The unipolar barrier detector exhibits reduced dark current densities and full bandgap activation energies whereas the photodiode exhibits orders of magnitude larger dark current and a reduced activation energy.

Figure 3 demonstrated that the new unipolar device design has dramatically reduced dark currents at all temperatures examined, and has dark currents that reduce much more efficiently when cooling.

3. Conclusions

Modeling was developed to describe the dependence of detectors' dark current on defect concentration and temperature, for both the traditional pn-based devices and the newly developed unipolar barrier devices. The model was verified with experimental measurements.

Unipolar barrier devices, under elevated defect concentrations, show elevated dark currents but remain diffusion limited (full bandgap thermal activation energies) unlike conventional pn junction based photodiodes under similar defect concentrations that show significantly higher dark currents and a reduced activation energy. Unipolar barrier detectors under moderate or high defect concentrations are limited by defect-related minority generation in the quasi-neutral absorber, but are subject to two different dependences on the defect density depending on the diffusion length and the thickness of the absorbing region.

In cases where defect concentrations are significant, *e.g.,* mismatched epitaxial material or radiation damaged material, unipolar barrier devices exhibit superior performance in terms of the magnitude of the dark current and the efficiency of dark current reduction by cooling.

4. Papers Published

"Dark current filtering in unipolar barrier infrared detectors," G.R. Savich, J.R. Pedrazzani, D.E. Sidor, S. Maimon, and G.W. Wicks, Appl. Phys. Lett **99**, 121112 (2011)

"Benefits and limitations of unipolar barriers in infrared photodetectors," G.R. Savich, J.R. Pedrazzani, D.E. Sidor, G.W. Wicks, Infrared Physics & Technology **59**, 152 (2013)

"nBn dark current reduction by UV hydrogenation," M. Jain, J.R. Pedrazzani, T.G. Golding, R. Cottier, O.W. Holland, R. Hellmer, G.W. Wicks, Infrared Physics & Technology 59, 156 (2013)

"Defect related dark currents in III-V MWIR nBn detectors", G. R. Savich, D. E. Sidor, X. Du, M. Jain, C. P. Morath, V. M. Cowan, J. K. Kim, J. F. Klem, D. Leonhardt, S. D. Hawkins, T. R. Fortune, A. Tauke-Pedretti, G. W. Wicks, Proc. of SPIE 9070, 907011 (2014)

"Effect of defects on III-V MWIR nBn detector performance," G. R. Savich, D. E. Sidor, C. P. Morath, V. M. Cowan, G. W. Wicks, Proc. SPIE 9226, 92260R-1 (2014)

5. Students Graduated

Gregory Savich, PhD, 2014

Department Of Defense

Defense Technical Information Center
8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, VA 22060-6201
ATTN: DTIC/OCA

Defense Threat Reduction Information Analysis
Center 8725 John J. Kingman Road, Suite 0944
Ft. Belvoir, VA 22060-6201
ATTN: DTRIAC

Defense Threat Reduction Agency
8725 John J. Kingman Road
Ft. Belvoir, VA 22060-6201
ATTN: Jacob Calkins