REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 13-10-2014	2. REPORT TYPE Conference Proceeding	3. DATES COVERED (From - To) -

4. TITLE AND SUBTITLE
Effect of defects on III-V MWIR nBn detector performance

5a. CONTRACT NUMBER
W911NF-11-1-0378

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Edward W. Taylor, David A. Cardimona, G. R. Savich, D. E. Sidor, X. Du, C. P. Morath, V. M. Cowan, G. W. Wicks

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Rochester
518 Hylan Bldg.

Rochester, NY 14627 -0140

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)
60124-EL.5

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

Under elevated defect concentrations, MWIR, III-V nBn detectors exhibit diffusion limited performance with elevated dark current densities. The resulting diffusion current is limited by the generation of carriers through defect states in the neutral n-type absorber and a dark current dependence on the defect density described by one of two limits, a short absorber or long absorber limit. This characteristic contrasts that exhibited by defect limited, conventional pn junction based photodiodes which exhibit performance limited by Shockley-Read-Hall generation

15. SUBJECT TERMS
infrared detectors, MWIR, nBn, photodiode, defects, irradiation, lattice mismatch, dark current

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Gary Wicks
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		19b. TELEPHONE NUMBER 585-275-4867

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

Report Title

Effect of defects on III-V MWIR nBn detector performance

ABSTRACT

Under elevated defect concentrations, MWIR, III-V nBn detectors exhibit diffusion limited performance with elevated dark current densities. The resulting diffusion current is limited by the generation of carriers through defect states in the neutral n-type absorber and a dark current dependence on the defect density described by one of two limits, a short absorber or long absorber limit. This characteristic contrasts that exhibited by defect limited, conventional pn junction based photodiodes which exhibit performance limited by Shockley-Read-Hall generation in the depletion layer rather than diffusion based processes.

Conference Name: SPIE Optical Engineering + Applications

Conference Date: August 28, 2014

Effect of defects on III-V MWIR nBn detector performance

G. R. Savich[a], D. E. Sidor[a], X. Du[a], C. P. Morath[b], V. M. Cowan[b], G. W. Wicks*[a]
[a]The Institute of Optics, University of Rochester, 275 Hutchison Rd, Rochester, NY 14627-0186, USA; [b]Air Force Research Laboratory, Space Vehicles Directorate, 3550 Aberdeen Ave SE, Kirtland AFB, NM, USA 87117

ABSTRACT

Under elevated defect concentrations, MWIR, III-V nBn detectors exhibit diffusion limited performance with elevated dark current densities. The resulting diffusion current is limited by the generation of carriers through defect states in the neutral n-type absorber and a dark current dependence on the defect density described by one of two limits, a short absorber or long absorber limit. This characteristic contrasts that exhibited by defect limited, conventional pn junction based photodiodes which exhibit performance limited by Shockley-Read-Hall generation in the depletion layer rather than diffusion based processes.

Keywords: infrared detectors, MWIR, nBn, photodiode, defects, irradiation, lattice mismatch, dark current.

1. INTRODUCTION

1.1 Barrier Architecture Detectors with Elevated Defect Concentrations

Barrier architecture detectors have shown considerable promise as an alternative to conventional structures for high performance infrared detection since the nBn was first introduced[1]. The ability of these detector structures to naturally suppress some dark current mechanisms, such as surface leakage current, generation-recombination current generated in depletion layers, and tunneling currents, is a significant advantage; however, performance matching or exceeding Rule 07 has not been achieved[2,3]. This suggests that barrier architecture detectors have not exhibited Auger limited performance [4].

One consideration that may contribute to this elevated dark current is a high defect concentration as the introduction of defects typically increases dark currents. There are several possible sources of defects in compound semiconductor-based detectors. In some cases, defects can be grown into the structure either as defects directly grown into the bulk crystal lattice, dislocations from growth on mismatched substrates, or layer interface defects in type-II strained layer superlattices. In some applications for MWIR detection, devices may operate in environments in which exposure to radiation is a concern. In this case, even a high performance detector may become severely defect limited as irradiation causes a significant reduction in performance[5]. As elevated dark currents will increase noise in the detector, it is important to understand the impact elevated defect concentrations will have on barrier architecture detector performance.

2. GENERATION – RECOMBINATION CURRENTS IN PHOTODETECTORS

The Shockley-Read-Hall (SRH) theory for generation-recombination in semiconductor structures provides a useful description of the effects defects have on dark currents generated in depletion regions and neutral regions of semiconductors[6,7]. Each of these regions exhibit a different current characteristic and varying dark current dependencies on the defect density.

*wicks@optics.rochester.edu; phone 1 585 275-4867; fax 1 585 244-4936

Nanophotonics and Macrophotonics for Space Environments VIII, edited by Edward W. Taylor,
David A. Cardimona, Proc. of SPIE Vol. 9226, 92260R · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2064229

2.1 Depletion Region Generation – Recombination Current

Conventional pn-junction based photodiodes are typically limited by Shockley-Read-Hall (SRH) generation in the depletion region[6,7]. For this case, the theory predicts a thermal activation energy of half the bandgap and a dark current density that is directly proportional to the defect density:

$$J_{Depletion} = C_1 e^{-E_g/2kT} N_{defect} \tag{1}$$

The half-bandgap thermal activation energy is typically observed in detectors that are defect limited in a given temperature range[8].

2.2 Neutral Region Generation – Recombination Current

Generation-Recombination currents may manifest in neutral regions of semiconductors when there is an elevated defect concentration. This effect is also described in Shockley's original theory[6,7]. The magnitude of neutral region SRH current is typically significantly lower than depletion region SRH currents and, thus, this mechanism has typically been less important even though both mechanisms will exist in defect limited pn-junction based devices. With the emergence of barrier architecture detectors, which do not exhibit depletion region SRH currents under reasonable biases, this neutral region SRH effect has greater significance.

The dark current density for neutral region SRH generation can be obtained by combining Shockley's neutral region generation with the diffusion of carriers. Two limits result from the diffusion theory including a short absorber or long diffusion length and a long absorber or short diffusion length limit. Each case exhibits a different dependence on the defect concentration and corresponds to a different magnitude of defect concentration in the device.

The short absorber limit can also be described as a long diffusion length case. Here, the diffusion length is longer than the thickness of the absorber region. This is the optimum arrangement for high quantum efficiency infrared detectors as it guarantees that the highest percentage of photogenerated carriers are collected at the contacts before recombination can occur. The characteristics of the dark current density for this case are generally described by:

$$J_{short,abs}^{Neutral} = C_2 e^{-E_g/kT} N_{Defect} \tag{2}$$

In the short absorber limit for neutral region generation, the dark current density due to defects maintains a full bandgap thermal activation energy, and is directly proportional to the defect density.

The long absorber limit describes performance when the absorber thickness is greater than the diffusion length. The performance in this case varies slightly from the previous case, primarily when it comes to the dependence on defect density. The general dark current density characteristics for the long absorber or short diffusion length limit follow:

$$J_{long,abs}^{Neutral} = C_2 e^{-E_g/kT} \sqrt{N_{Defect}} \tag{3}$$

Like the short absorber limit, the thermal activation energy for the long absorber follows the full bandgap energy, but now, the dark current density is proportional to the square root of the defect density. This indicates that when a device enters the long absorber limit, further increasing the defect concentration will have a smaller effect on the increasing dark current density when compared to a device operating in the short absorber limit.

2.3 Short and Long Absorber Limits in Practice

High performance MWIR detectors typically exhibit long diffusion lengths far in excess of the absorber thickness. These high quantum efficiency, non-defect limited detectors will operate in the short absorber limit. In this case, there will be some low level defect related dark current, but it will be small compared to the limiting current, typically Auger generation current and subsequent diffusion of carriers. This Auger limited performance has not yet been demonstrated in III-V barrier architecture detectors.

In nBn detectors with a moderate increase in defect concentration the limiting diffusion current may remain in the short absorber limit where the diffusion length is still long relative to the thickness of the absorber but the performance is now limited by defect induced neutral region SRH generation. To date, this is the best that has been achieved for barrier architecture detectors indicated by dark current densities above those predicted by Rule 07[3,4].

Detectors with very high defect concentrations may enter the short diffusion length regime or long absorber limit, where the diffusion length is now shorter than the thickness of the absorber. In this case, barrier architecture devices will be limited by neutral region SRH currents in accordance with long absorber limited diffusion. Even though this limit exhibits a reduced dependence of the dark current on increasing defect density, this limit suggests that significant damage has been done to the epitaxial structure and thus should be avoided if at all possible.

Ideally, it is best to operate a device in a low defect concentration state where the limiting current mechanism is not defect related. If defects cannot be avoided, it is better to minimize the accumulated defects and remain in the short absorber limit where degradation in performance is minimized.

3. DARK CURRENT DEPENDENCE ON DEFECT DENSITY

It has been shown that the defect concentration due to the lattice-mismatch scales inversely with the buffer layer thickness, thus InAs pn junction photodiodes were grown on both lattice matched and lattice mismatched substrates[9]. The photodiodes were grown via molecular beam epitaxy on InAs, InP, and GaAs substrates and the InAs buffer thicknesses were varied on the InP and GaAs substrate growths. Dark current characteristics were collected and dark current density was plotted against the inverse of the buffer thickness (figure 1).

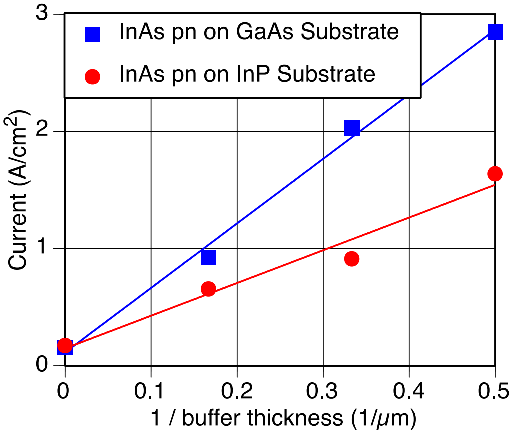

Figure 1. Current density vs. reciprocal buffer thickness for InAs pn junction photodiodes on mismatched substrates. The induced defect density shares a direct proportionality with the reciprocal of the buffer thickness and thus the dark current density scales directly with increasing defect concentration.

Lattice matched InAs photodiodes are indicated as points with zero reciprocal buffer thickness. The linear relationship between current density and reciprocal buffer thickness indicates a direct proportionality between dark current density and increases in defect concentration as predicted by the SRH theory for generation in depletion regions of pn-junction based devices.

Proton irradiated nBn detectors have been considered. In the case of barrier architecture detectors, the neutral region SRH and diffusion model predicts one of two behaviors manifest in two different dependences on the defect concentration. It is useful to consider the predicted behavior of dark current as a function of proton fluence (figure 2).

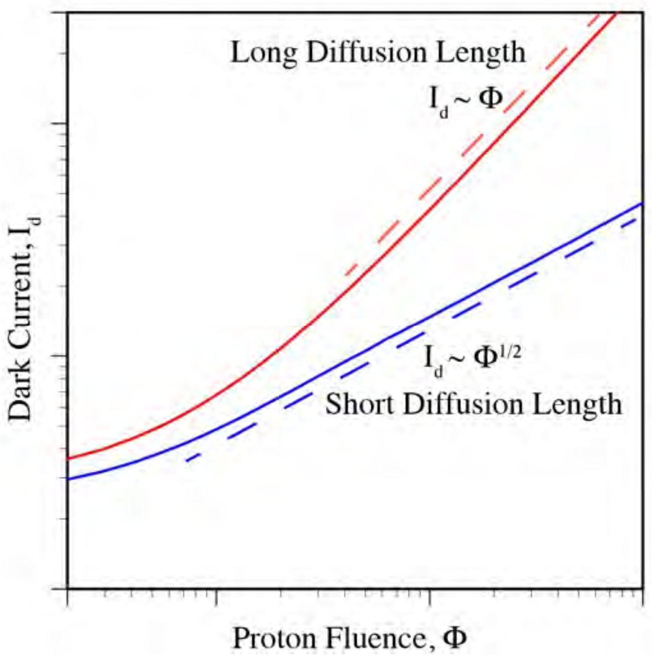

Figure 2. Predicted relationship between dark current and proton fluence for both the long diffusion length case or short absorber limit and the short diffusion length case or long absorber limit. In both cases, low fluence levels show dark currents limited by native defects in the epitaxial structure before radiation damage significantly increases the dark current. At higher fluence levels, dark current either scales directly with or with the square root of the proton fluence for the long and short diffusion length cases respectively.

Figure 2 shows predicted performance under increasing proton fluence for both the long diffusion length case, or short absorber limit, and the short diffusion length, or long absorber limit. In both cases, under low fluences the model predicts performance limited by native defects in the epitaxial structure. These defects are already inherent in the crystal structure before any irradiation occurs. Low fluence levels do not significantly increase the defect concentration and thus the dark current density. Under moderate to high proton fluences, the defect concentration increases enough to cause an increase in the dark current. It is assumed that defect concentration increases linearly with proton fluence. Here, the difference in proportionality between dark current and defect density in the two limits can be seen. The long diffusion length limit will show a direct proportionality between dark current and proton fluence while the short diffusion length limit shows that dark current is proportional to the square root of the proton fluence.

A superlattice, MWIR nBn detector was irradiated with 63 MeV protons at a low operating temperature[8]. The dark current is plotted against proton fluence in figure 3.

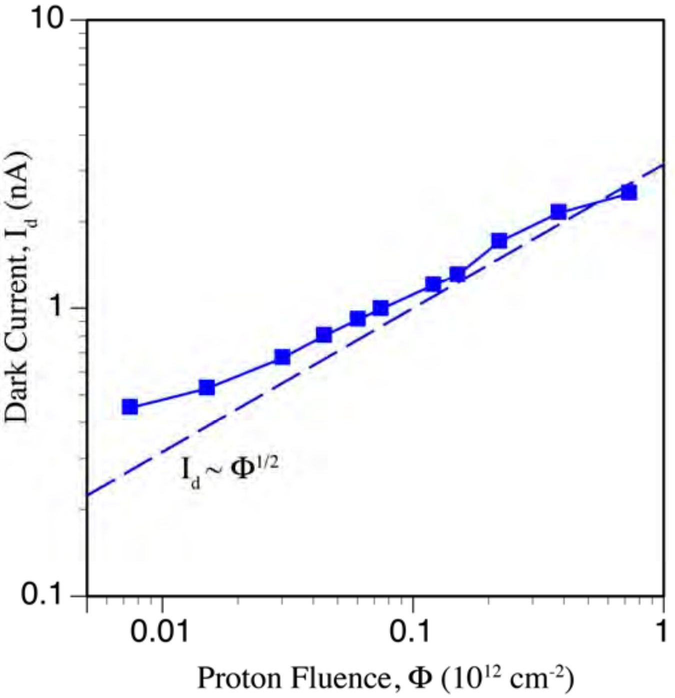

Figure 3. Dark current as a function of proton fluence for a proton irradiated MWIR nBn photodetector. Under low fluence levels, performance of the detector is primarily limited by native defects in the epitaxial structure. Higher fluence levels indicate dark current is proportional to the square root of the defect density indicating performance in the short diffusion length or long absorber limit.

Under low proton fluence levels, there is only a minimal increase in the dark current indicating that low proton fluences are not significantly increasing the defect concentration beyond the native defect concentration of the epitaxial structure in accordance with the model and figure 2. Moderate to high proton fluences, however, do result in a noticeable increase in dark current with increasing proton fluence. Under these conditions, the dark current increases with the square root of the proton fluence meaning the dark current is proportional to the square root of the defect density. This indicates that the device is operating in the short diffusion length regime where the absorber is thicker than the diffusion length. The native defects of this growth were high enough that this device was operating in the short diffusion length limit even before irradiation of the device. If the epitaxial growth of the device yielded a lower native defect concentration, it is likely the detector would have had a longer diffusion length and would have operated in the long diffusion length limit, even under moderate proton fluences.

4. CONCLUSIONS

The manner in which defects increase dark currents in photodetectors is dependent on both device architecture and defect concentrations. Conventional pn junction-based photodiodes under high defect levels follow the SRH model for generation in the depletion region of a pn junction while barrier architecture detectors, particularly the nBn, show defect limited performance in accordance with SRH generation in the neutral region followed by the diffusion of carriers. For the nBn, one of two cases may dominate. The long diffusion length limit where the absorber thickness is shorter than the diffusion length indicates low defect or moderate defect levels and defect related currents will scale directly with increases in defect density. For higher defect concentrations, the diffusion length becomes shorter than the absorber thickness indicating the short diffusion length limit. Here, the dark current scales as the square root of the defect density; however, this limit indicates significant damage to the semiconductor structure and thus reduced performance.

ACKNOWLEDGEMENT

The authors wish to acknowledge JK Kim, JF Klem, D Leonhardt, SD Hawkins, TR Fortune, and A Tauke-Pedretti of Sandia National Laboratories in Albuquerque, New Mexico for the design, growth, and fabrication of the MWIR nBn used for the irradiation study.

REFERENCES

[1] Maimon, S. and Wicks, G.W., “nBn detector, an infrared detector with reduced dark current and higher operating temperature,” Appl. Phys. Lett. 89 (15), 151109 (2006).
[2] Pedrazzani, J.R., Maimon, S., and Wicks, G.W., “Use of nBn structures to suppress surface leakage currents in unpassivated InAs infrared photodetectors,” Electron Lett. 44 (25), 1487 (2008).
[3] Savich, G.R., Pedrazzani, J.R., Sidor, D.E., Maimon, S., Wicks, G.W., “Dark current filtering in unipolar barrier infrared detectors,” Appl. Phys. Lett. 99 (12), 121112 (2011).
[4] Tennant, W.E., Lee, D., Zandian, M., Piquette, E., and Carmody, M., “MBE HgCdTe Technology: A Very General Solution to IR Detection, Described by ‘Rule 07’, a Very Convenient Heuristic,” Journal of Electronic Materials 37 (9), 1406 (2008).
[5] Cowan, V.M., Morath, C.P., Hubbs, J.E., Myers, S., Plis, E., Krishna, S., “Radiation tolerance characterization of dual band InAs/GaSb type-II strain-layer superlattice pBp detectors using 63 MeV protons,” Appl. Phys. Lett. 101 (25), 251108 (2012).
[6] Shockley, W., Read, Jr., W.T., “Statistics of the recombinations of holes and electrons.” Phys. Rev. 87 (5), 835 (1952).
[7] Sah, C.-T, Noyce, R.N., Shockley, W., “Carrier generation and recombination in p-n junctions and p-n junction characteristics,” Proc. IRE 45 (9), 1228 (1957).
[8] GR Savich, DE Sidor, X Du, M Jain, CP Morath, VM Cowen, JK Kim, JF Klem, D Leonhardt, SD Hawkins, TR Fortune, A Tauke-Pedretti, GW Wicks, “Defect Related Dark Currents in III-V MWIR nBn Detectors,” SPIE Defense+ Security, 907011-907011-6 (2014).
[9] Krier, A., Suleiman, W., “Uncooled photodetectors for the 3-5µm spectral range based on III-V heterojunctions,” Appl. Phys. Lett. 89 (8), 083512 (2006).