GROWTH AND CHARACTERIZATION STUDIES OF ADVANCED INFRARED HETEROSTRUCTURES

Sanjay Krishna

University of New Mexico 1313 Goddard SE Albuquerque, NM 87106

30 Jun 2015

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.



AIR FORCE RESEARCH LABORATORY Space Vehicles Directorate 3550 Aberdeen Ave SE AIR FORCE MATERIEL COMMAND KIRTLAND AIR FORCE BASE, NM 87117-5776

DTIC COPY

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report is the result of contracted fundamental research deemed exempt from public affairs security and policy review in accordance with SAF/AQR memorandum dated 10 Dec 08 and AFRL/CA policy clarification memorandum dated 16 Jan 09. This report is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RV-PS-TR-2015-0126 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNED// CHRISTIAN MORATH Program Manager

//SIGNED//

PAUL D. LEVAN, Ph.D. Technical Advisor, Space Based Advanced Sensing and Protection

//SIGNED//

JOHN BEAUCHEMIN Chief Engineer, Spacecraft Technology Division Space Vehicles Directorate

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

ADDIT CONSTRAINT AND ADDITION OF THE ADDITION OF ADDITIONAL ADDITION OF ADDITIONAL ADDI	REPORT DOCUMENTATION PAGE					Form Approved		
data under advancements and events the solucity of the solucit	Public reporting burden for this	mated to average 1 hour per res	oonse, including the time for revie	ewing instructions, sear	ching existing data sources, gathering and maintaining the			
State is not elemented is any offer source of the is used to any peak for bining to analy with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any and with a categor of the indication and any any and any and any and any any and any and any and any and any any and any any and any any any and any any and any	data needed, and completing a this burden to Department of D	and reviewing this collection of i refense, Washington Headquar	nformation. Send comments reg ters Services, Directorate for Info	arding this burden estimate or ar rmation Operations and Reports	iy other aspect of this c (0704-0188), 1215 Jeff	ollection of information, including suggestions for reducing erson Davis Highway, Suite 1204, Arlington, VA 22202-		
	4302. Respondents should be	aware that notwithstanding an	y other provision of law, no perso	n shall be subject to any penalty	for failing to comply wit	h a collection of information if it does not display a currently		
30-06-2015 Final Report 15 Feb 2013 - 90 May 2014 4-TTLE AND SUBTILE Go Way 2014 Growth And Characterization Studies Of Advanced Infrared Heterostructures Feb 2013 - 90 May 2014 4-TTLE AND SUBTILE 56. GRANT NUMBER Growth And Characterization Studies Of Advanced Infrared Heterostructures 56. GRANT NUMBER 6. AUTHOR(5) 2181 Sunjay Krishna 56. PROGRAM ELEMENT NUMBER 7. PERFORMING ORGANIZATION NAME(5) AND ADDRESS(E5) 56. PENOGRAM ELEMENT NUMBER 131 Godata SE Albuquerque, NM 87106 9. SPONSORING / MONITORING AGENCY NAME(5) AND ADDRESS(E5) 8. PERFORMING ORGANIZATION REPORT 133 Godata SE Albuquerque, NM 87106 9. SPONSORING / MONITORING AGENCY NAME(5) AND ADDRESS(E5) 8. PERFORMING ORGANIZATION REPORT AIF Force Research Laboratory 9. SPONSORMONITOR'S ACRONYM(5) Space Vehicles Directorate 3530 Aberden Ave, SE Stringuition / Availability Statement AFRL/RVSS 11. SPONSORMONITOR'S ACRONYM(6) AFRL/RVSS 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. 13. Supplementary NOTES 11. SPONSORMONITOR'S ACRONYMES 14. AESTRACT The goal of this project was to invest	1. REPORT DATE (DL	D-MM-YY)	2. REPORT TYPE	KE35.	3	3. DATES COVERED (From - To)		
4. TITLE AND SUBTITLE S. CONTRACT NUMBER Growth And Characterization Studies Of Advanced Infrared Heterostructures S. CONTRACT NUMBER FA9453-13-1-0234 5b. GRAIT NUMBER Sanjay Krishna S. PROGRAM ELEMENT NUMBER Sanjay Krishna S. CONTRACT NUMBER Off Control Contrecont Contrecont Control Control Control Contrecont Co	30-06-2015		Final Report			15 Feb 2013 – 09 May 2014		
Growth And Characterization Studies Of Advanced Infrared Heterostructures FA9453-13-1-0284 50. GRANT NUMBER 6. AUTHOR(S) 6. AUTHOR(S) 5. anjay Krishna FARCIENT NUMBER 5. TASK NUMBER 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 7. PERFORMING ORGANIZATION REPORT 10. SPONSOR/MONITOR'S ACRONYM(S) 7. PERFORMING ORGANIZATION REPORT 13. SUPPLEMENTARY NOTES 7. PERFORMING ORGANIZATION PERFORMING ORGANIZATION REPORT 14. ABSTRACT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS(ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION REPORT 7. PUBLIC PLANE AND ADDRESS (ES) 7. PERFORMING ORGANIZATION PLANE (ES) 7. PONSOR/MONITOR'S ACRONYM(S) 7. PERFORMING ORGANIZATION PLANE (ES) 7. PERFORMING PROVIDES 7. PERFORMIN	4. TITLE AND SUBTIT	LE				5a. CONTRACT NUMBER		
FA9453-13-1-0284 50. GRANT NUMBER 52. PROGRAM ELEMENT NUMBER 54011F 6. AUTHOR(5) Sanjay Krishna 57. TERFORMING ORGANIZATION NAME(5) AND ADDRESS(ES) University of New Mexico 1313 Goldand SE Albuquerque, NM 87106 9. SPONSOR/MONITORING AGENCY NAME(5) AND ADDRESS(ES) Albuquerque, NM 87106 9. SPONSOR/MONITORING AGENCY NAME(5) AND ADDRESS(ES) Albuquerque, NM 87106 9. SPONSOR/MONITORING AGENCY NAME(5) AND ADDRESS(ES) Albuquerque, NM 87106 9. SPONSOR/MONITOR'S ACRONYM(5) AFRL /R V/SS 71. SPONSOR/MONITOR'S ACRONYM(5) 72. DISTRIBUTION / AVAILABILTY STATEMENT APRL -RV-PS-TR-2015-0126 </td <td>Growth And Charac</td> <td>terization Studies Of</td> <td>Advanced Infrared H</td> <td>eterostructures</td> <td></td> <td></td>	Growth And Charac	terization Studies Of	Advanced Infrared H	eterostructures				
5b. GRANT NUMBER 5c. AUTHOR(S) Sanjay Krishna 5c. FROGRAM ELEMENT NUMBER 2181 Sanjay Krishna 5c. TASK NUMBER PROGRAM ELEMENT NUMBER 2181 Sanjay Krishna 5c. TASK NUMBER PROGRAM ELEMENT NUMBER 2181 Son GRANIZATION NAME(S) AND ADDRESS(ES) University of New Mexico 1313 Goldard SE Alhuquerque, NM 87106 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Ali Force Research Laboratory Space Vehicles Directorate 3550 Aberdeen Ave, SE Kritland AFB, NM 87117-5776 10. SPONSOR/MONTOR'S ACRONYM(S) AFRL-RV-PS-TR-2015-0126 11. SPONSOR/MONTOR'S REPORT NUMBER(S) AND ADDRESS(ES) 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors The goal of this project was to investigate band structure engineering in infared detectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons fo					1	FA9453-13-1-0284		
6. AUTHOR(\$) 5. PROGRAM ELEMENT NUMBER G3401F 5. AUTHOR(\$) 5. PROGRAM ELEMENT NUMBER G3401F 5. Sanjay Krishna 5. Second Number 2181 6. AUTHOR(\$) 5. FROET NUMBER 2181 5. TPERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) 5. WORK UNIT NUMBER PPM00020523 1313 Goldand SE Albuquerque, NM 87106 8. PERFORMING ORGANIZATION REPORT NUMBER 1313 Goldand SE Albuquerque, NM 87106 9. PERFORMING ORGANIZATION REPORT NUMBER 550 Abreden Ave., SF Kirtland AFB, NM 87117-5776 10. SPONSOR/MONITOR'S ACRONYM(\$) AFRL/RVSS 13. SUPPLEMENTARY NOTES 11. SPONSOR/MONITOR'S ACRONYM(\$) AFRL/RVSS 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlatice detectors (T2SL3). The origin of high dark current levels in the InAs/In(Ga)SD T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier Inferime core dark current, Shockley-Read-Hall, SRH, superlattice core- superlattices, type II 16. SECURITY CLASSIFICATION OF: ARSTRACT Unlimited 18. NUMBER Definition Morath 19. TELEPHONE NUMBER (induce arms core)								
6. AUTHOR(\$) S. AURHOR(\$)						D. GRANT NOMBER		
6. AUTHOR(\$) Sad01F Sd 01F Sd 01F Sd 01F 6. AUTHOR(\$) Sd 0FD02CT NUMBER 2181 Sanjay Krishna Sd 7002CT NUMBER 2181 5. TPERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) St 70000 CE18000 CGANIZATION REPORT University of New Mexico 1313 Goldand SE St 70000 CE18000 CGANIZATION REPORT Albuquerque, NM 87106 S. PERFORMING ORGANIZATION RAGENCY NAME(\$) AND ADDRESS(E\$) N. SPONSOR/MONITOR'S ACRONYM(\$) Air Force Research Laboratory Space Vehicles Directorate AFRL/RVSS 350 Aberdeen Ave., SE T1. SPONSOR/MONITOR'S REPORT NUMBER(\$) AFRL/RVSS AFRL/RVSS AFRL/RVSS 350 Aberdeen Ave., SE T1. SPONSOR/MONITOR'S REPORT NUMBER(\$) AFRL-RV-PS-TR-2015-0126 HI. SPONSOR/MONITOR'S REPORT NUMBER(\$) AFRL-RV-PS-TR-2015-0126 HI. SPONSOR/MONITOR'S REPORT NUMBER(\$) 13. SUPPLEMENTARY NOTES He major reasons for the high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 75. SUBJECT TERMS T1. INITATION OF ABSTRACT T9. NUMBER PERSON								
6. AUTHOR(S) Sal PROJECT NUMBER Sanjay Krishna Sal PROJECT NUMBER 2181 Se. TASK NUMBER PPM00020523 6f. WORK UNIT NUMBER EF125606 S. TASK NUMBER PPM001020523 6f. WORK UNIT NUMBER EF125606 S. EASK NUMBER PPM0020523 6f. WORK UNIT NUMBER EF125606 S. EPERFORMING ORGANIZATION RAME(S) AND ADDRESS(ES) Albuquerque, NM 87106 10. SPONSORNO / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Alir Force Research Laboratory F. DEFFORMING ORGANIZATION REPORT Space Vehicles Directorate 11. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RVSS AFRL/RVSS Space Vehicles Directorate 11. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RVS NUMBER(S) J2. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. 13. SUPPLEMENTARY NOTES 11. SPONSOR/MONITOR'S REPORT 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlatice detectors (72SLs). The corigin of high dark current levels in the InAs/In(Ga)Sb T2SL infared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of t						53/01F		
8. ADMON(6) 2181 Sanjay Krishna 5. TODEC MORECK 2181 5. TASK NUMBER FP125696 5. TASK NUMBER FP125696 5. PERFORMING ORGANIZATION NAME(5) AND ADDRESS(ES) University of New Mexico 1313 Goldand SE Albuquerque, NM 87106 8. PERFORMING ORGANIZATION REPORT S. SPONSORING / MONTORING AGENCY NAME(5) AND ADDRESS(ES) 10. SPONSORMONTOR'S ACRONYM(5) Air Force Research Laboratory AFRL/RVSS Space Vehicles Directorate 350 Aberdeen Ave., SB 350 Aberdeen Ave., SB 11. SPONSORMONITOR'S REPORT Value of for public release; distribution is unlimited. 11. SPONSORMONITOR'S REPORT 13. SUPPLEMENTARY NOTES AFRL-RV-PS-TR-2015-0126 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors 14. ABSTRACT The goal of this project was to investigate them innority carrier lifetime and have been identified as one of the major reasons for the high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Inclassified 17. LIMITATION OF PERPONSIBLE PERSON <td></td> <td></td> <td></td> <td></td> <td></td> <td></td>								
Sanjay Krishna For TASK NUMBER PPM00020523 5. TASK NUMBER PPM00020523 5. TASK NUMBER PPM00020523 7. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) 8. PENDENING ORGANIZATION REPORT NUMBER 1313 Goddard SE Albuquerque, NM 87106 8. PONSOR/MONITOR'S ACRONYM(\$) Air Force Research Laboratory Space Vehicles Directorate 350 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776 10. SPONSOR/MONITOR'S ACRONYM(\$) AFRL-RV-PS-TR-2015-0126 12. DETRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. 11. SPONSOR/MONITOR'S REPORT NUMBER(\$) AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime cor> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 19a. NAME OF RESPONSIBLE PERSON Christian Morath 16. SECURITY CLASSIFICATION OF: Unclassified 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER 22 19a. NAME OF RESPONSIBLE PERSON Christian Morath</or>	0. AUTHOR(3)					181		
Saligay Krisma Joint Construction Saligay Krisma Joint Construction Jail Goldand SE Joint Construction Jail Goldand SE Albuquerque, NM 87106 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Is. SPONSOR/MONITOR'S ACRONYM(S) Air Force Research Laboratory Space Vehicle Directorate JS50 Aberdeen Ave., SF. Is. SPONSOR/MONITOR'S REPORT Kirtland AFB, NM 8717-5776 Is. SPONSOR/MONITOR'S REPORT 12. DISTRIBUTION / AVAILABILITY STATEMENT AFRL-RV-PS-TR-2015-0126 Approved for public release; distribution is unlimited. AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES Is. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared photodetectors was to be investigated. The presence of Shockley-Read-Hall entrak signade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TEMS 17. LIMITATION OF PROSE Image: Prove Prose Prosection Prove Pr	Contractive Variations							
1100000000000000000000000000000000000	Sanjay Krisnna					PPM00020523		
13. Goldard SE Albquerque, NM 87106 8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Albquerque, NM 87106 10. SPONSORING ORGANIZATION REPORT NUMBER 3. SPONSORING / MONTORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Space Vehicles Directorate 3550 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776 10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RVSS 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)SB T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL, material. 16. SUBJECT TERMS Carrier lifetime <or> Carrier lifetime <or> Carrier lifetime <or> ARC VERSE 13. NUMBER (Inclassified) 13. NUMBER (Inclassified) 13. NUMBER (Inclassified) 13. NUMBER (Inclassified)</or></or></or>					-			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION REPORT University of New Mexico 1313 Goddard SE 1313 Goddard SE 10. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory 5. SPONSOR/MONITOR'S ACRONYM(S) Space Vehicles Directorate 350 Aberdeen Ave., SE Stiftaland AFB, NM 87117-5776 11. SPONSOR/MONITOR'S ACRONYM(S) 12. DISTRIBUTION / AVAILABILITY STATEMENT AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors 17. SPLANE 13. SUPPLEMENTARY NOTES 15. SUBJECT TERMS Carrier lifetime Carrier lifetime Carrier lifetime 16. SECURITY CLASSIFICATION OF: 17. LINITATION 17. LINITATION 18. NUMBER 18. SECURITY CLASSIFICATION OF: 17. LINITATION 19. AMBC OF RESPONSIBLE PERSON Christian Morath 19. AMBC OF RESPONSIBLE PERSON Christian Morath 19. ADMEER 19. ADMEER (produce area 19. ADMEER Contacte area 19. ADMEER (produce area Contacte area						FF125696		
1. FUNCTION 1. EXAMPLE INTERVIEW 13.13 Goddard SE 1. SUMBER 13.13 Goddard SE 1. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Ait Force Research Laboratory AFRL/RVSS Space Vehicles Directorate 3550 Aberdeen Ave., SE Strittand AFB, NM 87117-5776 11. SPONSOR/MONITOR'S REPORT VILL Distribution / AVAILABILITY STATEMENT AFRL/RV-PS-TR-2015-0126 Approved for public release; distribution is unlimited. AFRL/RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 4. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall acters degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS 17. LIMITATION OF ABSTRACT 18. NUMBER 19a. NAME OF RESPONSIBLE PERSON 16. SECURITY CLASSIFICATION OF: 17. LIMITATION Unclassified 18. NUMBER 19a. NAME OF RESPONSIBLE PERSON 17. LIMITATION Unclassified 0. ABSTRACT 0. FHIS PAGE 22 22								
University of New Mexico 1313 Goddard SE Albuquerque, NM 87106 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Space Vehicles Directorate 350 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlatice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL. material. 15. SUBJECT TERMS Carrier lifetime <or> 4rement of T2SL material. 16. SEURITY CLASSIFICATION OF: 17. LIMITATION 18. AUMBER 19a. NAME OF RESPONSIBLE PERSON 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ADME OF RESPONSIBLE PERSON 19. TELEPHONE NUMBER (include area</or>	7. FERFORMING ORC	JANIZATION NAME(3)	AND ADDRESS(ES)			NUMBER		
1313 Goddard SE Albuquerque, NM 87106 Io. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AIF FOCR Research Laboratory Space Vehicles Directorate 3500 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776 Io. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RVSS 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release: distribution is unlimited. JAFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES II. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RV-PS-TR-2015-0126 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> Carrier lifetime <or> Garier lifetime <or> Grade URL SIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 19a. NAME OF RESPONSIBLE PERSON Christian Morath 16. SECURITY CLASSIFICATION OF: 17. LIMITATION Unclassified 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19. TELEPHONE NUMBER (metude area oode) 22 Code /</or></or></or>	University of New M	/lexico				-		
Albuquerque, NM 87106 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Space Vehicles Directorate 3550 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776 11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL/RVSS AFRL/RV	1313 Goddard SE							
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) Air Force Research Laboratory AFRL/RVSS Space Vehicles Directorate 11. SPONSOR/MONITOR'S ACRONYM(S) AFRL/RVSS AFRL/RVSS Sitting and AFB, NM 87117-5776 11. SPONSOR/MONITOR'S REPORT 12. DISTRIBUTION / AVAILABILITY STATEMENT AFRL-RV-PS-TR-2015-0126 Approved for public release; distribution is unlimited. 4FRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAx/In(Ga)Sb T2SL. infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS 17. LIMITATION OF Corporation OF absTRACT 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER (Include area 19a. NAME OF RESPONSIBLE PERSON Christian Morath a. REPORT Unclassified Unlimited 22 20. Diverse Date 1. Diverse Date 22	Albuquerque, NM 8	7106						
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Space Vehicles Directorate 3550 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776 10. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RV-PS-TR-2015-0126 11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 16. SUBJECT TERMS Carrier lifetime <arrively-superlattice <or=""> 16. SUBJECT TERMS Carrier lifetime <arrively-superlattice <or=""> 17. LIMITATION 0F ABSTRACT Unclassified Unclassified Unclassified C. THIS PAGE Unlimited 0. ABSTRACT 0. A</arrively-superlattice></arrively-superlattice>								
Air Force Research Laboratory AFRL/RVSS Space Vehicles Directorate Harden Ave., SE Kirtland AFB, NM 87117-5776 1. SPONSOR/MONITOR'S REPORT 12. DISTRIBUTION / AVAILABILITY STATEMENT AFRL-RV-PS-TR-2015-0126 APRL-RV NOTES AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES Infared detectors based on Type II superlattice detectors 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors 17. SUBJECT TERMS Tarter lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 16. SUBJECT TERMS If a SUBJECT TERMS Carrier lifetime <or> are rent lifetime <or> b. ABSTRACT If a Directed as a current, Shockley-Read-Hall, SRH, superlattice <or> OF PAGES If a. NAME OF RESPONSIBLE PERSON Christian Morath Inclassified Unclassified Unclassified Unclassified Unlimited 22</or></or></or>	9. SPONSORING / MC	NITORING AGENCY N	AME(S) AND ADDRES	S(ES)	1	10. SPONSOR/MONITOR'S ACRONYM(S)		
Space Vehicles Directorate 11. SPONSOR/MONTOR'S REPORT 3550 Aberdeen Ave., SE 11. SPONSOR/MONTOR'S REPORT Kirtland AFB, NM 87117-5776 11. SPONSOR/MONTOR'S REPORT 12. DISTRIBUTION / AVAILABILITY STATEMENT AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime Carrier lifetime Shockley-Read-Hall, SRH, superlattice 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 0. ABSTRACT Unclassified 0. ABSTRACT Unclassified 0. ABSTRACT Unclassified 0. ABSTRACT 0. ABSTRACT 0. THIS PAGE 0. ALL or of the order of the core of the core of the second the area	Air Force Research	Laboratory			1	AFRL/RVSS		
3550 Aberdeen Ave., SE Kirdand AFB, NM 87117-5776 11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RV-PS-TR-2015-0126 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES Unlimited 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area origin)	Space Vehicles Dire	ctorate						
Kirtland AFB, NM 87117-5776 NUMBER(S) AFRL-RV-PS-TR-2015-0126 12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> Carrier lifetime <or> Are Current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: Unclassified 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES Unlimited 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19. D. TELEPHONE NUMBER (include area code) 19b. TELEPHONE NUMBER (include area code) 22</or></or></or>	3550 Aberdeen Ave	SE			1	11. SPONSOR/MONITOR'S REPORT		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. AFRL-RV-PS-TR-2015-0126 13. SUPPLEMENTARY NOTES 13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs.). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: Unclassified 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES Unlimited 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code)</or></or>	Kirtland AFB. NM	., ~				NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. 1.000000000000000000000000000000000000	, , ,					AFRL-RV-PS-TR-2015-0126		
Approved for public release; distribution is unlimited.	12. DISTRIBUTION / A	VAILABILITY STATE	IENT					
13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <orb <or="" current,="" dark="" shockley-read-hall,="" srh,="" superlattice=""> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION of ABSTRACT Unclassified Unclassified b. ABSTRACT Unclassified C. THIS PAGE Unclassified Unclassified Unclassified 0. ABSTRACT Correct Corr</orb>	Approved for public	release; distribution	is unlimited.					
13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: a. REPORT 0. ABSTRACT Unclassified 0. THIS PAGE Unclassified 0. ABSTRACT Unclassified 0. THIS PAGE Unlimited 22</or></or>	11 1							
13. SUPPLEMENTARY NOTES 14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION Unclassified 18. NUMBER OF ABSTRACT Unclassified 19. ABSTRACT Unclassified 10. ABSTRACT Unclassified 11. LIMITATION Unclassified 12. Current I and the structure of the presence of the structure of the presence of the presence</or></or>								
14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II </or> 16. SECURITY CLASSIFICATION OF: 0F ABSTRACT 0r ABSTRACT <td< td=""><td>13. SUPPLEMENTAR</td><td>Y NOTES</td><td></td><td></td><td></td><td></td></td<></or>	13. SUPPLEMENTAR	Y NOTES						
14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> <or> carrier lifetime <or> <or> ors > dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 0F ABSTRACT 0F PAGES Unclassified b. ABSTRACT Unclassified C. THIS PAGE Unclassified Unclassified Unclassified C. THIS PAGE Unclassified Duclassified Unclassified Duclassified Unclassified Duclassified Unclassified Duclassified</or></or></or></or></or>								
14. ABSTRACT The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime vortential. 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 0F ABSTRACT 0F ABSTRACT Unclassified 0. ABSTRACT Unclassified 0. ABSTRACT C. THIS PAGE Unlimited 22 22								
The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II If a number of T2SL material. 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT OF ABSTRACT Unclassified 19a. NAME OF RESPONSIBLE PERSON Christian Morath a. REPORT b. ABSTRACT Unclassified C. THIS PAGE Unclassified Unlimited 22 Unclassified 0. Detection of the core 0. Christian Morath 0. Christian Morath</or></or>	14. ABSTRACT							
(T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared photodetectors was to be investigated. The presence of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime Image: Subject terms and the set of term and te	The goal of this proj	ect was to investigat	e band structure engir	eering in infared dete	ctors based on	Type II superlattice detectors		
of Shockley-Read-Hall centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified b. ABSTRACT Unclassified c. THIS PAGE Unclassified Variation 22</or></or>	(T2SLs). The origin	of high dark current	levels in the InAs/In(Ga)Sb T2SL infrared	photodetectors	was to be investigated. The presence		
dark current of T2SL material. 15. SUBJECT TERMS 15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19. ABSTRACT Unclassified C. THIS PAGE Unclassified 18. NUMBER Unclassified 19. ABSTRACT Unclassified C. THIS PAGE Unclassified 19. NAME OF RESPONSIBLE PERSON Christian Morath 22 20</or></or>	of Shockley-Read-H	all centers degrade t	he minority carrier lif	etime and have been i	dentified as one	e of the major reasons for the high		
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES Unclassified 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code) 22</or></or>	dark current of T2SI	_ material.	,			5 6		
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES Unlimited 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code)</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES Unlimited 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code)</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified b. ABSTRACT Unclassified c. THIS PAGE Unclassified C. THIS PAGE Unclassified Unlimited 22</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: a. REPORT Unclassified b. ABSTRACT Unclassified c. THIS PAGE Unclassified Unclassified c. THIS PAGE Unclassified Unclassified Unclassified C. THIS PAGE Unclassified Unclassified Unclassified Unclassified Unclassified Unclassified Unclassified Unclassified</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code)</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code) 19b. TELEPHONE NUMBER (include area code)</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code)</or></or>								
15. SUBJECT TERMS Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath 19b. TELEPHONE NUMBER (include area code)</or></or>								
Carrier lifetime <or> dark current, Shockley-Read-Hall, SRH, superlattice <or> superlattices, type II 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath a. REPORT Unclassified b. ABSTRACT Unclassified c. THIS PAGE Unclassified Unlimited 22 19b. TELEPHONE NUMBER (include area code)</or></or>	15. SUBJECT TERMS							
16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath a. REPORT Unclassified b. ABSTRACT Unclassified c. THIS PAGE Unclassified Unlimited 22 19a. NAME OF RESPONSIBLE PERSON Christian Morath	Carrier lifetime <or:< td=""><td>> dark current, Shock</td><td>ley-Read-Hall, SRH,</td><td>superlattice <or> sup</or></td><td>erlattices, type</td><td>II</td></or:<>	> dark current, Shock	ley-Read-Hall, SRH,	superlattice <or> sup</or>	erlattices, type	II		
16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Christian Morath a. REPORT Unclassified b. ABSTRACT Unclassified c. THIS PAGE Unclassified Unlimited 22 19b. TELEPHONE NUMBER (include area code)								
a. REPORT b. ABSTRACT c. THIS PAGE Unclassified Uncla	16. SECURITY CLASS	SIFICATION OF:		17. LIMITATION	18. NUMBER	19a. NAME OF RESPONSIBLE PERSON		
a. REPORT b. ABSTRACT c. THIS PAGE Unclassified Unclassified Unclassified Unclassified Unclassified Unclassified 22 19b. TELEPHONE NUMBER (include area code)				OF ADDIKALI	UF PAGES	Christian Morath		
Unclassified Unclassified Unclassified Unlimited 22 ^{code}	a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area		
	Unclassified	Unclassified	Unclassified	Unlimited	22	coae)		

Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std. 239.18

(This page intentionally left blank)

TABLE OF CONTENTS

Section

Page

List of Figures and Tables	ii
1 Summary	1
2 Introduction	1
3 Methods, Assumptions, and Procedures	3
4 Results and Discussions	4
5 Conclusions	10
References	11
APPENDIX	12
LIST OF ACRONYMS	13

LIST OF FIGURES

Figure

Page 1

1.	Band diagram of a (simplified) mid-IR interband cascade photodetector relevant
	envelop wave-functions and their energy levels are also shown2
2.	The dark current density of themed-IR interband cascade detectors as functions of bias
	voltages at various temperatures. Each of the operation temperatures is labeled near the
	<i>J-V</i> curves
3.	The Arrhenius plots of the electrical perfomances of the ICIPs, the dark current density
	(measured at -50 mV) as well as zero-bias resistance-area-product under various
	temperatures are shown
4.	Optical performances of the interband cascade devices under various operation
	temperatures7
5.	Measured signal-to-noise ratio as a function of bias voltage at various temperatures.
	The detectors were illuminated using a 1000 K blackbody, the signal modulated by
	an optical chopper placed in front of the cryostat
6.	Johnson-noise limited D^* spectra of sample 6eB at various temperatures. The
	background-limited operation temperature is estimated to be around 150K9

<u>Table</u>

Page

1. Electrical and optical performances of the mid-wave ICIPs......9

ACKNOWLEDGMENTS

This material is based on research sponsored by Air Force Research Laboratory under agreement number FA9453-13-1-0284. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

DISCLAIMER

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of Air Force Research Laboratory or the U.S. Government.

(This page intentionally left blank)

1 SUMMARY

The goal of this project was to investigate band structure engineering in infared detectors based on Type II superlattice detectors (T2SLs). The origin of high dark current levels in the InAs/In(Ga)Sb T2SL infrared (IR) photodetectors was to be investigated. The presence of Shockley-Read-Hall (SRH) centers degrade the minority carrier lifetime and have been identified as one of the major reasons for the high dark current of T2SL material. The ultimate goal of the program is to decrease the dark current and thereby increase the operating temperature of T2SL detectors through a systematic study involving the growth, fabrication and characterization of T2SL detectors.

This was a very successful project with barrier engineering in interband cascade superlattice detectors and quantum dots in a well detector. The first interband cascade focal plane array (FPA) was reported as a result of this work. There were a total of seven publications that resulted from partial support from this work.

2 INTRODUCTION

We report our experimental investigation on the influence of electron barriers (eBs) in mid-IR interband cascade photodetectors. Even though earlier theoretical projection indicates that an eB with 2-pairs of GaSb/AlSb quantum wells (QWs) is sufficient to block electrons directly tunneling between stages, our experimental results show that a thicker electron barrier (with 6-pairs of GaSb/AlSb QWs) could significantly reduce the device dark current, with little influence on the optical performance. Interband cascade devices with a five stage absorber have demonstrated a dark current density of 8.32×10^{-7} A/cm² (at -50 mV), which is within a factor of 2 of the Rule 07 and a Johnson-limited *D** of 1.81×10^{11} cmHz^{1/2}/W (at 3.8 µm) at 150K.

Antimony-based T2SLs are being recognized as a viable/competitive alternative to HgCdTe for high-performance IR imaging systems [1]. For the past several years, T2SL technology has received considerable amount of scientific and technological interest. Owing to the great flexibility/versatility of energy band alignment in the nearly lattice-matched "6.1-Å-family" (InAs, GaSb, AlSb, and their alloys) [2], and reduced Auger recombination rate and heavier electron effective masses, various advanced T2SL-based photodetector architectures have been implemented, leading to significantly improved detector performances [3-10]. Among them are the double heterostructures with graded-gap W-structure [3] and M-structure [4], as well as unipolar-barrier detectors [5-6], complementary-barrier IR detectors [7], and interband cascade IR photodetectors (ICIPs) [8-10]. The interband cascade detector has three regions and the principle of operation is shown in Fig. 1. The first is the absorber region in which photo-excited carriers are generated, the second is a hole barrier (hB) that allows transport through electron relaxation and the third is an electron barrier (eB) that enables tunneling into the next stage [10]. The hB typically consists of coupled multi-quantum wells (MQWs), such that a series of staircase energy ladders is formed in the conduction band. In our design, a type-II broken-gap band alignment between the hB and eB is adopted. Such a design facilitates a fast carrier relaxation path for photo-generated electrons, leading to efficient collection of photo-generated carriers [9-10]. As schematically shown in Fig. 1, due to the existence of the eB on one side (right) of the absorber, combined with the fast relaxation channel at the other side (left), such a preferential

electron transport path (left to right in Fig. 1) enables an interband cascade device to have a junction-like rectification behavior and photovoltaic operation [9-11]. The cascade (or multijunction) scheme has introduced an additional degree of freedom/flexibility for T2SL-based IR detector design, and could potentially open a new dimension for IR photodetector design. While some preliminary experimental results have shown the promising prospect of interband cascade photodetectors, some of the fundamental device physics remains unclear. In such a relatively complicated structure, understanding the underlying device physics as well as finding the optimized design parameters is critical.



Figure 1. Band diagram of a (simplified) mid-IR interband cascade photodetector relevant envelop wave-functions and their energy levels are also shown.

Figure 1 also shows the structure has been modified for better presentation. The incoming photons are absorbed in the InAs/GaSb SL absorber, generating electron-hole pairs. The electrons will diffuse into the electron relaxation region, and then effectively transport into the valence band of the next stage, through fast longitudinal-optical-phonon-assisted, intraband relaxation and also interband tunneling.

3 METHODS, ASSUMPTIONS, and PROCEDURES

In this project, we examined the influence of electron barrier design on the electrical and optical performance of mid-IR interband cascade detectors. As reported in Ref. 10, theoretical investigations based on a two-band k p model suggest that the estimated direct tunneling time across the double GaSb/AlSb QW is longer than 100 µs. Even though a substantially improved electrical performance was reported and mainly attributed to the "enhanced electron barrier", no qualitative investigations or comparisons were made. It is still unclear whether such a relatively thin electron barrier (~ 17 nm), as compared to typical unipolar barrier designs ($\sim 100-200$ nm), is sufficient to block the carriers from passing through. This is especially the case since other transport paths, such as trap-assist tunneling and thermionic emissions, were not included in the modeling. Besides, whether a thicker eB would hinder the photo-carrier transport or would be helpful to properly implement the interband cascade photodetector design needs to be determined. Here, we report our experimental investigation, on the influence of the thickness of the electron barrier on both the electrical and optical performances in mid-IR interband cascade detectors. Devices with different electron barrier thicknesses were designed, grown, fabricated, characterized and analyzed in detail. It was concluded that a thicker electron barrier was instrumental in reducing the dark current, while having no impact on the strength of the optical signal.

The wafers were grown on Zn-doped 2" (001) GaSb substrates with a Veeco Gen-10 solidsource molecular beam epitaxy system, equipped with group III sources and valved group V crackers. The epi-structure starts with a 0.5 µm p-type GaSb buffer layer, followed by a 5-stage interband cascade structure with moderately thin InAs/GaSb T2SL as absorber, and terminated with a 45-nm-thick *n*-type InAs top contact layer. Each cascade stage is composed of 30-periods (~140 nm) of non-intentionally doped InAs/GaSb [~6 ML/9 ML (ML = monolayer)] SL absorber, sandwiched between the electron-relaxation and the eB regions. The electronrelaxation region is composed of InAs/Al(In)Sb coupled MQWs to form a stair-case energy ladder in the conduction band, and the separation between adjacent energy levels is designed to be close to the longitudinal-optical-phonon energy [10]. As indicated in Fig. 1, the uppermost energy level in the first InAs QW is close to the conduction miniband in the InAs/GaSb SL, and the bottom energy-level in the final InAs well is positioned below the valence-band edge of the adjacent GaSb layer in the eB region, allowing the interband tunneling of extracted carriers into the next stage. The eB consists of GaSb/AISb MQWs, and the estimated barrier height in the conduction band is ~0.68 eV. The other role of the GaSb/AlSb MQWs is also the need to facilitate hole transport (in the valence band) towards the type-II broken-gap interface. Three samples with different eB thickness were implemented. Their electron barriers consist of 2-pair, 4-pair, and 6-pair of GaSb/AlSb QWs (the samples will be denoted as 2eB, 4eB, and 6eB hereafter), with each layer thicknesses slightly adjusted for smooth hole transport. The nominal thicknesses of the eB layers are 17, 33 and 48 nm for the 2eB, 4eB and 6eB samples, respectively.

4 RESULTS and DISCUSSION

After growth, the epitaxial wafers were characterized by x-ray diffraction to monitor crystal quality and layer thicknesses. The estimated InAs/GaSb SL periods are about 47.7 Å (2.1% thicker than designed), with full width half maximum of around 30 arc-seconds. The overall strain is controlled within 50 arc-seconds for all the samples. The three samples were then processed into deep-etched mesa-type photodiodes, by using standard contact ultraviolet lithography and wet-chemical etching. The circular mesa-size ranged from 25 to 400 μ m in diameter. A 200-nm-thick SiN_x film was then deposited for sidewall passivation and isolation. Top and bottom contacts were formed by e-beam evaporated Ti/Au. No anti-reflectance coating was applied on top of the mesa. Devices were mounted on ceramic leadless chip carriers, and then mounted in the cryostat to characterize their optical and electrical properties.

The electrical performances of the three ICIP devices are characterized over a wide range of temperatures. The dark current densities at -50 mV are as low as 4.24 nA/cm² at 80 K and 0.83 μ A/cm² at 150 K which is comparable to the reported state-of-the-art values [12]. Note that the dark current at lower temperatures could be overestimated due to the setup limitation and imperfect cold shielding. Figure 2 shows the dark current density of the three ICIP devices as a function of voltage at various temperatures. As indicated in the figure, at lower temperatures, devices with thicker eB have significantly lower dark current, particularly under higher operating bias. We believe that such a steeper slope with respect to the operation bias could be an indication that tunneling might be one of the primary dark current components in the thinner devices. As the temperature increases, the difference becomes marginal, which could be an indication that the generation-recombination (G-R) or diffusion current is becoming dominate at higher temperatures.



Figure 2. The dark current density of the mid-IR interband cascade detectors as functions of bias voltages at various temperatures. Each of the operation temperatures is labeled near the *J*-*V* curves.

Figure 3 shows the Arrhenius plot of dark current density at -50 mV as well as the dynamic resistance-area product (R_0A) of three samples. As one can see from Fig. 3, the sample with the thicker eB shows appreciable influence on the dark current density for temperatures up to 280 K, even under lower operating bias. The dark current density is 9.27×10^{-9} A/cm² for the 6eB sample at 100 K, and 4.35×10^{-8} A/cm² for the 2eB sample. The R_0A of the 6eB sample exceeds $6.15 \times 10^7 \ \Omega \text{cm}^2$ at 100 K (42 times higher compared with the 2eB sample), and $2.10 \times 10^4 \ \Omega \text{cm}^2$ at 150 K (over 3-times higher than the 2eB sample), which is also comparable to the reported state-of-the-art T2SL detectors [12]. The dark current is as low as 1.98×10^{-6} A/cm² at 160 K, which is a factor of two greater than the dark current predicted for HgCdTe by "Rule 07" [13]. At temperatures higher than 280 K, the device performances start to converge as the dark current is less sensitive to the eB thicknesses. As stated earlier, the marginal difference attributed to the dark current is mostly due to G-R or diffusion components.



Figure 3. The Arrhenius plots of the electrical performances of the ICIPs, the dark current density (measured at -50 mV) as well as zero-bias resistance-area-product under various temperatures are shown.

The response spectra were obtained from a Fourier-transform IR spectrometer, and were calibrated by radiometric measurements with a black-body at 1000 K. Figure 4a shows the calibrated optical responsivity spectra of samples under zero-bias at various temperatures. The 100% cut-off wavelength of the ICIPs is around 4.2 µm at 80 K, and 4.8 µm at 300 K. The relatively low responsivity is attributed to the relatively thin absorber (the total thickness is 0.7 μ m) and the 1/N (N is the number of stages) photoconductive gain inherently due to the interband cascade scheme [9]. As seen in Fig. 4b, the responsivities of the ICIPs at zero-bias are around 0.10 A/W at 3.6 µm and 80 K, then gradually decrease down to 0.08 A/W around 160 K, and then ramp up to 0.13 A/W at temperatures up to 360 K. The thin lines with smaller symbols in Fig. 4b are the responsivities of each of the devices at moderately high reverse bias where the response at 3.6 µm starts to saturate. The saturation responsivity increased from ~0.11 A/W at 80 K, which corresponds to an absorption quantum efficiency of 13.3%, to ~ 0.13 A/W at 200 K. It is believed that the decrease of zero-bias responsivity at moderate temperatures is due to the background carrier concentration change and p-type to n-type inversion [14]. Such change could introduce some band-bending, which would alter the band alignment and could produce unwanted carrier blocking barriers and deteriorate the zero-bias photo-carrier transport. With the

assistance of a stronger reverse bias, more photo-carriers will be collected with the aid of drift, resulting in a monotonic increase in the saturated responsivity.



Figure 4. Optical performances of the interband cascade devices under various operation temperatures.

In Figure 4 (a) the response spectra measured at zero-bias at different temperatures and (b) the zero-bias responsivity at 3.6 and 4.0 μ m as a function of operation temperature. The saturated R_i at 3.6 μ m at lower temperatures are also shown.

In contrast to unipolar barrier detectors, which are typically operated at a slight reversed bias (around -0.1 to -0.3 V) for optimum signal-to-noise ratio (SNR), the efficient carrier extraction under zero-bias enables ICIPs to be operated at zero-bias. As shown in Figure 5, even with the un-optimized design, where the signal under zero-bias is only 55-68% of its saturation value, the maximized SNR is obtained under zero-bias. This could be advantageous for IR detection, especially for high temperature operations.



Figure 5. Measured signal-to-noise ratio as a function of bias voltage at various temperatures. The detectors were illuminated using a 1000 K blackbody, the signal modulated by an optical chopper placed in front of the cryostat.

Even with the relatively low responsivity, the improved electrical performances in the ICIP devices lead to improved values of the signal-to-noise ratio and detectivity. Figure 6 is the Johnson-noise limited detectivity spectra for sample 6eB under various temperatures, extracted from the measured responsivity spectra and R_0A . The Johnson-noise limited D^* reaches 8.62×10^{12} Jones at 3.8 µm and 80 K, and 9.73×10^{10} Jones at 160 K. Table 1 summarizes the optical and electrical performance of all samples at different temperatures. The dark current density at -50 mV is 4.57×10^{-5} A/cm² at 200 K, and the extracted R_0A is 983 Ω cm², corresponding to a Johnson-noise limited D^* of 2.40×10^{10} Jones at 3.8 µm. Preliminary attempts of 320×256 FPAs were made on the 4eB and 6eB samples. The FPAs were operational at temperatures up to 150 K, with noise-equivalent temperature differences as low as 20 mK at 80 K. Further investigations are underway and will be reported elsewhere.



Figure 6. Johnson-noise limited D^* spectra of sample 6eB at various temperatures. The background-limited operation temperature is estimated to be around 150 K.

	-											
	Device 2eB			Device 4eB			Device 6eB					
T (K)	$\begin{array}{c} J_D @-\\ 50 \mathrm{mV}\\ \mathrm{(A/cm^2)} \end{array}$	$R_0 A$ ($\Omega \mathrm{cm}^2$)	<i>R_i</i> @4μm (A/W)	$D^*_{Johnson}$ (Jones)	J _D @- 50mV (A/cm ²)	$R_0 A$ ($\Omega \mathrm{cm}^2$)	<i>R_i</i> @4μm (A/W)	$D^*_{Johnson}$ (Jones)	J _D @- 50mV (A/cm ²)	$R_0 A$ (Ωcm^2)	<i>R_i</i> @4μm (A/W)	D [*] _{Johnson} (Jones)
150	2.71E-6	1.20E4	0.085	1.08E11	1.66E-6	2.56E4	0.070	1.47E11	8.32E-7	4.99E4	0.073	2.22E11
200	1.23E-4	4.61E2	0.107	2.18E10	7.63E-5	5.84E2	0.082	1.88E10	4.57E-5	9.83E2	0.090	2.67E10
300	2.53E-2	1.77	0.143	1.48E9	1.88E-2	2.39	0.132	1.74E9	1.90E-2	2.38	0.132	1.58E9

Table. 1 Electrical and optical performances of the mid-wave ICIPs.

5 CONCLUSIONS

In summary, the influence of electron barrier design, on the electrical and optical properties of mid-IR interband cascade photodetectors, was evaluated. Our experimental investigations showed that the further enhancement of the electron barrier will significantly reduce the device dark current, with little influence on optical performance. Our results also indicate that a slightly-doped InAs/GaSb T2SL would reduce the influence of background carrier concentration variation with temperature, and would be preferential for consistent temperature behavior. Further investigation is required to find the optimum electron barrier designs. The improvements in the electrical performance have led to substantial performance improvements. An R_0A of 4990 Ω cm² and Johnson-limited D^* of 1.82×10^{11} cmHz^{1/2}/W at 3.8 µm at 150 K were obtained. It is believed that the great versatility of the interband cascade photodetectors could be further explored for application-targeted optimization and high performance IR imaging applications.

REFERENCES

- 1. A. Rogalski, J. Antoszewski, and L. Faraone, "Third-generation infrared photodetector arrays," J. Appl. Phys. 105,091101 (2009).
- 2. H. Kroemer, "The 6.1 angstrom family (InAs, GaSb, AlSb) and its heterostructures: a selective review," *Physica E* **20**, 196, (2004).
- 3. I. Vurgaftman, E.H. Aifer, C.L. Canedy, J.G. Tischler, J.R. Meyer, J.H. Warner, E.M. Jackson, G. Hildebrandt, and G.J. Sullivan, "Graded band gap for dark-current suppression in long-wave infrared W-structured type-II superlattice photodiodes," *Appl. Phys. Lett.* **89**, 121114 (2006).
- 4. B.-M. Nguyen, M. Razeghi, V. Nathan, and G.J. Brown, "Type-II M structure photodiodes: an alternative material design for mid-wave to long wavelength infrared regimes," *Proc. SPIE* **6479**, 64790S (2007).
- 5. S. Maimon, and G.W. Wicks, "nBn detector, an infrared detector with reduced dark current and higher operating temperature," *Appl. Phys. Lett.* **89**, 151109 (2006).
- 6. B.-M. Nguyen, S. Bogdanov, S. Abdollahi Pour, and M. Razeghi, "Minority electron unipolar photodetectors based on type II InAs/GaSb/AlSb superlattices for very long wavelength infrared detection," *Appl. Phys. Lett.* **95**, 183502 (2009).
- D.Z.-Y. Ting, C.J. Hill, A. Soibel, S.A. Keo, J.M. Mumolo, J. Nguyen, and S.D. Gunapala, "A high-performance long wavelength superlattice complementary barrier infrared detector," *Appl. Phys. Lett.* 95, 023508 (2009).
- 8. J.V. Li, R.Q. Yang, C.J. Hill, and S.L. Chuang, "Interband cascade detectors with room temperature photovoltaic operation," *Appl. Phys. Lett.* **86**, 101102 (2005).
- 9. R.Q. Yang, Z. Tian, Z. Cai, J.F. Klem, M.B. Johnson, and H.C. Liu, "Interband-cascade infrared photodetectors with superlattice absorbers," *J. Appl. Phys.* **107**, 054514 (2010).
- Z. Tian, R.T. Hinkey, R.Q. Yang, Y. Qiu, D. Lubyshev, J.M. Fastenau, Amy W.K. Liu, and M.B. Johnson, "Interband cascade infrared photodetectors with enhanced electron barriers and p-type superlattice absorbers," *J. Appl. Phys.* **111**, 024510 (2012).
- 11. R.Q. Yang, Z. Tian, J.F. Klem, T.D. Mishima, M.B. Santos, and M.B. Johnson, "Interband cascade photovoltaic devices," *Appl. Phys. Lett.* **96**, 063504 (2010).
- 12. S. Abdollahi Pour, E.K. Huang, G. Chen, A. Haddadi, B.-M. Nguyen, and M. Razeghi, "High operating temperature midwave infrared photodiodes and focal plane arrays based on type-II InAs/GaSb superlattices," *Appl. Phys. Lett.* **98**, 143501 (2011).
- 13. W.E. Tennant, ""Rule 07" Revisited: Still a Good Heuristic Predictor of p /n HgCdTe Photodiode Performance?" *J. Electron. Mater.* **39**, 1030 (2010).
- 14. C. Cervera, J.B. Rodriguez, J.P. Perez, H. Aït-Kaci, R. Chaghi, L. Konczewicz, S. Contreras, and P. Christol, "Unambiguous determination of carrier concentration and mobility for InAs/GaSb superlattice photodiode optimization," *J. Appl. Phys.* 106, 033709 (2009).

APPENDIX

Publications Resulting From This Effort

- 1. Tian, Z. B., Schuler-Sandy, T., & Krishna, S. (2013). Electron barrier study of mid-wave infrared interband cascade photodetectors. Applied Physics Letters, 103(8), 083501.
- Tian, Z. B., Godoy, S. E., Kim, H. S., Schuler-Sandy, T., Montoya, J. A., & Krishna, S. (2014). High operating temperature interband cascade focal plane arrays. Applied Physics Letters, 105(5), 051109.
- Tian, Z. B., Schuler-Sandy, T., Godoy, S. E., Kim, H. S., & Krishna, S. (2013, September). High-operating-temperature MWIR detectors using type II superlattices. In SPIE Optical Engineering+ Applications (pp. 88670S-88670S). International Society for Optics and Photonics.
- Tian, Z. B., Schuler-Sandy, T., Godoy, S. E., Kim, H. S., Montoya, J., Myers, S., & Krishna, S. (2013, June). Quantum-engineered mid-infrared type-II InAs/GaSb superlattice photodetectors for high temperature operations. In SPIE Defense, Security, and Sensing (pp. 87041T-87041T). International Society for Optics and Photonics.
- Acosta, L., Klein, B., Tian, Z. B., Frantz, E., Myers, S., Gautam, N., ... & Krishna, S. (2014, February). Investigation of quantum efficiency in mid-wave infrared (MWIR) InAs/GaSb type-II strained layer superlattice (T2SL) detectors. In SPIE OPTO (pp. 89960P-89960P). International Society for Optics and Photonics.
- Kim, J. O., Ku, Z., Kazemi, A., Urbas, A., Kang, S. W., Noh, S. K., ... & Krishna, S. (2014). Effect of barrier on the performance of sub-monolayer quantum dot infrared photodetectors. Optical Materials Express, 4(2), 198-204.
- Kim, J. O., Ku, Z., Krishna, S., Kang, S. W., Lee, S. J., Jun, Y. C., & Urbas, A. (2014). Simulation and analysis of grating-integrated quantum dot infrared detectors for spectral response control and performance enhancement. Journal of Applied Physics, 115(16), 163101.

LIST OF ACRONYMS

eB	electron	barrier

FPA	Focal plane array
G-R	generation-recombination
hB	hole barrier
ICIP	interband cascade infrared photodetectors
IR	Infrared
ML	monolayer
MQW	multi-quantum well
QW	quantum well
SRH	Shockley-Read-Hall
SNR	signal-to-noise ratio
T2SL	type-II superlattice

DISTRIBUTION LIST

DTIC/OCP	
8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/RVIL Kirtland AFB, NM 87117-5776	2 cys
Official Record Copy AFRL/RVSS/Christian Morath	1 cy