Proposal #
0000204279

U.S. Department of Energy
Office of Science

GrantsGov #
GRANT11249210

APPLICATION/PROPOSAL COVER SHEET

THE ATTACHED APPLICATION/PROPOSAL IS FOR YOUR REVIEW & APPROPRIATE ACTION

INSTITUTION: Radiation Monitoring Devices, Inc., Watertown, Massachusetts

TYPE OF REQUEST: New

P.I.: Johnson, Erik

DATE RECEIVED: 10/15/2012 5:14:17 PM

AWARD NO: N/A

SOLICITATION NO: DE-FOA-0000760

TITLE: 42a Low-Noise Solid State Photomultiplier for Dark Matter Studies

TOTAL NUMBER OF PAGES SUBMITTED: 72

ERROR LIST: No Errors

Table Of Contents

OMB Number: 4040-0001
Expiration Date: 06/30/2011

APPLICATION FOR FEDERAL ASSISTANCE
SF 424 (R&R)

3. DATE RECEIVED BY STATE

State Application Identifier

1. * TYPE OF SUBMISSION

☐ Pre-application ☒ Application ☐ Changed/Corrected Application

4. a. Federal Identifier

b. Agency Routing Identifier

2. DATE SUBMITTED 10/15/2012

Applicant Identifier P13-026

5. APPLICANT INFORMATION

*** Organizational DUNS:** 0738044110000

* Legal Name: Radiation Monitoring Devices, Inc.
Department: Research
Division:
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County / Parish:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* ZIP / Postal Code: 02472-4699

Person to be contacted on matters involving this application

Prefix: Ms.
* First Name: Marisa
Middle Name:
* Last Name: Eva
Suffix:
* Phone Number: 617-668-6817
Fax Number: 617-926-9980
Email: mekon@rmdinc.com

6. * EMPLOYER IDENTIFICATION *(EIN) or (TIN):* 26-2897516

7. * TYPE OF APPLICANT: R: Small Business

Other (Specify):

Small Business Organization Type ☐ Women Owned ☐ Socially and Economically Disadvantaged

8. * TYPE OF APPLICATION:

☒ New ☐ Resubmission
☐ Renewal ☐ Continuation ☐ Revision

If Revision, mark appropriate box(es).

☐ A. Increase Award ☐ B. Decrease Award ☐ C. Increase Duration ☐ D. Decrease Duration
☐ E. Other (specify):

* Is this application being submitted to other agencies? Yes ☐ No ☒ What other Agencies?

9. * NAME OF FEDERAL AGENCY: Office of Science

10. CATALOG OF FEDERAL DOMESTIC ASSISTANCE NUMBER: 81.049
TITLE: Office of Science Financial Assistance Program

11. * DESCRIPTIVE TITLE OF APPLICANT'S PROJECT:

42a Low-Noise Solid State Photomultiplier for Dark Matter Studies

12. PROPOSED PROJECT:
* Start Date: 02/01/2013
* Ending Date: 10/31/2013

*** 13. CONGRESSIONAL DISTRICT OF APPLICANT**
MA-007

14. PROJECT DIRECTOR/PRINCIPAL INVESTIGATOR CONTACT INFORMATION

Prefix:
* First Name: Erik
Middle Name:
* Last Name: Johnson
Suffix:
Position/Title: Scientist
* Organization Name: Radiation Monitoring Devices, Inc.
Department: Research
Division: Instrument Research and Dev.
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County / Parish:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* ZIP / Postal Code: 02472-4699
* Phone Number: 617-668-6801
Fax Number:
* Email: EJohnson@rmdinc.com

SF 424 (R&R) APPLICATION FOR FEDERAL ASSISTANCE

15. ESTIMATED PROJECT FUNDING

a. Total Federal Funds Requested	149,999.00
b. Total Non-Federal Funds	0.00
c. Total Federal & Non-Federal Funds	149,999.00
d. Estimated Program Income	0.00

16. * IS APPLICATION SUBJECT TO REVIEW BY STATE EXECUTIVE ORDER 12372 PROCESS?

a. YES ☐ THIS PREAPPLICATION/APPLICATION WAS MADE AVAILABLE TO THE STATE EXECUTIVE ORDER 12372 PROCESS FOR REVIEW ON:

DATE:

b. NO ☒ PROGRAM IS NOT COVERED BY E.O. 12372; OR

☐ PROGRAM HAS NOT BEEN SELECTED BY STATE FOR REVIEW

17. By signing this application, I certify (1) to the statements contained in the list of certifications* and (2) that the statements herein are true, complete and accurate to the best of my knowledge. I also provide the required assurances * and agree to comply with any resulting terms if I accept an award. I am aware that any false, fictitious. or fraudulent statements or claims may subject me to criminal, civil, or administrative penalities. (U.S. Code, Title 18, Section 1001)

☒ *** I agree**

**** The list of certifications and assurances, or an Internet site where you may obtain this list, is contained in the announcement or agency specific instructions.***

18. SFLLL or other Explanatory Documentation

Add Attachment | Delete Attachment | View Attachment

19. Authorized Representative

Prefix:
* First Name: Joanne
Middle Name:
* Last Name: Gladstone
Suffix:
* Position/Title: Vice President
* Organization: Radiation Monitoring Devices, Inc.
Department: Research
Division:
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County / Parish:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* ZIP / Postal Code: 02472-4699
* Phone Number: 617-668-6845
Fax Number: 617-926-9980
* Email: JGladstone@rmdinc.com

*** Signature of Authorized Representative**
Marisa Eva

*** Date Signed**
10/15/2012

20. Pre-application

Add Attachment | Delete Attachment | View Attachment

SBIR/STTR Information

OMB Number: 4040-0001
Expiration date: 06/30/2011

*** Program Type (select only one)**

☒ SBIR ☐ STTR
☐ Both *(See agency-specific instructions to determine whether a particular agency allows a single submission for both SBIR and STTR)*

*** SBIR/STTR Type (select only one)**

☒ Phase I ☐ Phase II
☐ Fast-Track *(See agency-specific instructions to determine whether a particular agency participates in Fast-Track)*

Questions 1-7 must be completed by all SBIR and STTR Applicants:

☒ Yes ☐ No	* 1a. Do you certify that at the time of award your organization will meet the eligibility criteria for a small business as defined in the funding opportunity announcement?
	* 1b. Anticipated Number of personnel to be employed at your organization at the time of award. 131
☐ Yes ☒ No	* 2. Does this application include subcontracts with Federal laboratories or any other Federal Government agencies? * If yes, insert the names of the Federal laboratories/agencies:
☐ Yes ☒ No	* 3. Are you located in a HUBZone? To find out if your business is in a HUBZone, use the mapping utility provided by the Small Business Administration at its web site: http://www.sba.gov
☒ Yes ☐ No	* 4. Will all research and development on the project be performed in its entirety in the United States? If no, provide an explanation in an attached file. * Explanation: Add Attachment Delete Attachment View Attachment
☐ Yes ☒ No	* 5. Has the applicant and/or Program Director/Principal Investigator submitted proposals for essentially equivalent work under other Federal program solicitations or received other Federal awards for essentially equivalent work? * If yes, insert the names of the other Federal agencies:
☒ Yes ☐ No	* 6. Disclosure Permission Statement: If this application does not result in an award, is the Government permitted to disclose the title of your proposed project, and the name, address, telephone number and e-mail address of the official signing for the applicant organization, to organizations that may be interested in contacting you for further information (e.g., possible collaborations, investment)?
	* 7. Commercialization Plan: If you are submitting a Phase II or Phase I/Phase II Fast-Track Application, include a Commercialization Plan in accordance with the agency announcement and/or agency-specific instructions. * Attach File: Add Attachment Delete Attachment View Attachment

SBIR/STTR Information

SBIR-Specific Questions:

Questions 8 and 9 apply only to SBIR applications. If you are submitting ONLY an STTR application, leave questions 8 and 9 blank and proceed to question 10.

☒ Yes ☐ No	* 8. Have you received SBIR Phase II awards from the Federal Government? If yes, provide a company commercialization history in accordance with agency-specific instructions using this attachment. * Attach File: 1250-Commercialization History. Add Attachment Delete Attachment View Attachment
☒ Yes ☐ No	* 9. Will the Project Director/Principal Investigator have his/her primary employment with the small business at the time of award?

STTR-Specific Questions:

Questions 10 and 11 apply only to STTR applications. If you are submitting ONLY an SBIR application, leave questions 10 and 11 blank.

☐ Yes ☐ No	* 10. Please indicate whether the answer to BOTH of the following questions is TRUE: (1) Does the Project Director/Principal Investigator have a formal appointment or commitment either with the small business directly (as an employee or a contractor) OR as an employee of the Research Institution, which in turn has made a commitment to the small business through the STTR application process; AND (2) Will the Project Director/Principal Investigator devote at least 10% effort to the proposed project?
☐ Yes ☐ No	* 11. In the joint research and development proposed in this project, does the small business perform at least 40% of the work and the research institution named in the application perform at least 30% of the work?

RESEARCH & RELATED Other Project Information

1. * Are Human Subjects Involved? ☐ Yes ☒ No

1.a If YES to Human Subjects

Is the Project Exempt from Federal regulations? ☐ Yes ☐ No

If yes, check appropriate exemption number. ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6

If no, is the IRB review Pending? ☐ Yes ☐ No

IRB Approval Date:

Human Subject Assurance Number:

2. * Are Vertebrate Animals Used? ☐ Yes ☒ No

2.a. If YES to Vertebrate Animals

Is the IACUC review Pending? ☐ Yes ☐ No

IACUC Approval Date:

Animal Welfare Assurance Number

3. * Is proprietary/privileged information included in the application? ☒ Yes ☐ No

4.a. * Does this project have an actual or potential impact on the environment? ☐ Yes ☒ No

4.b. If yes, please explain:

4.c. If this project has an actual or potential impact on the environment, has an exemption been authorized or an environmental assessment (EA) or environmental impact statement (EIS) been performed? ☐ Yes ☐ No

4.d. If yes, please explain:

5. * Is the research performance site designated, or eligible to be designated, as a historic place? ☐ Yes ☒ No

5.a. If yes, please explain:

6. * Does this project involve activities outside of the United States or partnerships with international collaborators? ☐ Yes ☒ No

6.a. If yes, identify countries:

6.b. Optional Explanation:

7. * Project Summary/Abstract `1242-P13_026_Summary.pdf` Add Attachment Delete Attachment View Attachment

8. * Project Narrative `1243-P13_026_Narrative.pdf` Add Attachment Delete Attachment View Attachment

9. Bibliography & References Cited `1244-P13_026_References.pdf` Add Attachment Delete Attachment View Attachment

10. Facilities & Other Resources `1245-P13_026_Facilities.pdf` Add Attachment Delete Attachment View Attachment

11. Equipment `1246-P13_026_Equipment.pdf` Add Attachment Delete Attachment View Attachment

12. Other Attachments Add Attachments Delete Attachments View Attachments ☒

Project/Performance Site Location(s)

Project/Performance Site Primary Location ☐ I am submitting an application as an individual, and not on behalf of a company, state, local or tribal government, academia, or other type of organization.

Organization Name: Radiation Monitoring Devices, Inc.
DUNS Number: 0738044110000
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* ZIP / Postal Code: 02472-4699
* Project/ Performance Site Congressional District: MA-007

Project/Performance Site Location 1 ☐ I am submitting an application as an individual, and not on behalf of a company, state, local or tribal government, academia, or other type of organization.

Organization Name: Brown University
DUNS Number: 0017855420000
* Street1: Dept. of Physics
Street2: Box 1843
* City: Providence
County:
* State: RI: Rhode Island
Province:
* Country: USA: UNITED STATES
* ZIP / Postal Code: 02912-0001
* Project/ Performance Site Congressional District: RI-001

Project/Performance Site Location 2 ☐ I am submitting an application as an individual, and not on behalf of a company, state, local or tribal government, academia, or other type of organization.

Organization Name: University of Virginia
DUNS Number: 0653915260000
* Street1: Department of Electrical and Computer Engineering
Street2: 351 McCormick Road PO Box 400743
* City: Charlottesville
County:
* State: VA: Virginia
Province:
* Country: USA: UNITED STATES
* ZIP / Postal Code: 22904-4743
* Project/ Performance Site Congressional District: VA-005

Budget Period: 1 Duration: 9 months	**DOE Funded Person-mos.**			**Funds Requested ($) (Salary+Fringe)**
	CAL	**ACAD**	**SUMR**	
A. Senior Personnel: PI/PO, Co-PI's, Faculty and Other Senior Associates **Total Senior Personnel (1-8)**				17,375.00
1. Johnson, Erik	0.72	0	0	5,827.00
2. Christian, James	0.27	0	0	3,192.00
3. Chen, Xiao Jie	1.08	0	0	8,356.00
4.				
5.				
6.				
7.				
8.				
9. Others (See Attachment for Details)				0.00
B. Other Personnel (Number in Brackets) **Total Other Personnel**				4,423.00
(0) Post Doctoral Associates				0.00
(0) Graduate Students				0.00
(0) Undergraduate Students				0.00
(0) Secretarial / Clerical				0.00
(1) Technician - Samuel Vogel	1.35			4,423.00
Total Personnel Costs **Total Salaries and Wages (A+B)**				21,798.00
C. Permanent Equipment **Total Permanent Equipment**				0.00
D. Travel **Total Travel**				3,386.00
1. Domestic Travel Costs (including Canada, Mexico, and U.S. possessions)				3,386.00
2. Foreign Travel Costs				0.00
E. Trainee/Participant Costs (Total Participants: 0) **Total Trainee/Participants**				0.00
1. Tuition/Fees/Health Insurance				0.00
2. Stipends				0.00
3. Trainee Travel				0.00
4. Subsistence				0.00
5. Other				0.00
F. Other Direct Costs **Total Other Direct Costs**				49,881.00
1. Materials and Supplies				7,181.00
2. Publication Costs/Documentation/Dissemination				0.00
3. Consultant Services				4,500.00
4. Computer (ADP) Services				0.00
5. SubAwards/Consortium/Contractual Costs				38,200.00
6. Equipment or Facility Rental/User Fees				0.00
7. Alterations and Renovations				0.00
8.				0.00
9.				0.00
10.				0.00
G. Direct Costs **Total Direct Costs (A through F)**				75,065.00
H. Indirect Costs **Total Indirect Costs**				65,121.00
		Indirect Cost Rate	**Indirect Cost Base**	
G&A:		40.00%	100,133.00	40,053.00
LO:		115.00%	21,798.00	25,068.00
I. Direct and Indirect Costs **Total Direct and Indirect Costs (G+H)**				140,186.00
J. Fee **Total Fee**				9,813.00
K. Cost of Project **Total Cost of Project (I+J)**				149,999.00

Cumulative Total	Subtotal	Totals ($)
Section A, Senior/Key Person		17,375.00
Section B, Other Personnel		4,423.00
Total Number Other Personnel	1	
Total Salary, Wages and Fringe Benefits (A+B)		21,798.00
Section C, Equipment		0.00
Section D, Travel		3,386.00
1. Domestic	3,386.00	
2. Foreign	0.00	
Section E, Participant/Trainee Support Costs		0.00
1. Tuition/Fees/Health Insurance	0.00	
2. Stipends	0.00	
3. Travel	0.00	
4. Subsistence	0.00	
5. Other	0.00	
Number of Participants/Trainees	0	
Section F, Other Direct Costs		49,881.00
1. Material and Supplies	7,181.00	
2. Publication Costs	0.00	
3. Consultant Services	4,500.00	
4. ADP/Computer Services	0.00	
5. Subawards/Consortium/Contractual Costs	38,200.00	
6. Equipment or Facility Rental/User Fees	0.00	
7. Alterations and Renovations	0.00	
8. Other 1	0.00	
9. Other 2	0.00	
10. Other 3	0.00	
Section G, Direct Costs (A thru F)		75,065.00
Section H, Indirect Costs		65,121.00
Section I, Total Direct and Indirect Costs (G+H)		140,186.00
Section J, Fee		9,813.00
Section K, Total Cost of Project (I+J)		149,999.00

Budget Justification

Dr. Eric Johnson, a senior scientist, has extensive experience with high-energy physics experiments, instrumentation, and calorimeters and will serve as the Principal Investigator on this project. He will dedicate 8% of his time toward the effort as a direct charge. He will oversee the research and development effort. He has experience in the fabrication of scintillation detectors, and has successfully directed various SBIR research programs. He will coordinate the research effort with the subcontractors and consultants at the University of Virginia and Brown University. Dr. Johnson is a U.S. citizen. Dr. Johnson has been budgeted for a total of 120 hours at the rate of $48.56 per hour for the program.

Dr. James F. Christian is the director for the Instrument Research and Development Group at RMD. He will dedicate 3% of his effort toward the project. During the Phase-1 period of the program, he will guide the migration of RMD's APD process toward the developments of SSPM detectors and the investigation of SiC as a candidate SSPM material. Dr. Christian is a U.S. citizen. Dr. Christian has been budgeted for a total of 40 hours at the rate of $79.81 per hour.

Dr. Jie Chen is a Staff Scientist in the IRD group at RMD with an expansive background in electrical engineering and the design of silicon and CMOS devices. He will assist in designing the GPD elements and will perform simulations of the SiC GPD devices using Silvaco. He will devote 12% of his time to this project. Dr. Chen is a lawful permanent resident of the United States. Dr. Chen has been budgeted for a total of 190 hours at the rate of $43.75 per hour.

Mr. Samuel Vogel will serve as a technician for this program. He will assist in the migration of process technologies to SSPM architectures in silicon and SiC. Mr Vogel has been budgeted for a total of 230 hours at the rate of $19.23 per hour.

These aforementioned participants will be a direct charge to the program.

Materials and supplies: The Phase-1 effort requires materials for testing process steps for both silicon and SiC devices. These materials consist of wafers, photo-resist, lithography masks, and reagents. We will also need coupons for the simulations run using Silvaco. An amount of $7,112 is required for the materials and run-time coupons.

Travel and related costs:

RMD anticipates sending one person to Washington, DC, for two days, to meet with the DOE program manager(s) and one person present results at the IEEE NSS/MIC meeting in 2013, 5 days, which will be held in Seoul, Korea. The per diem, $1,526, is based on the prices in the U.S. General Services Administration website, GSA.gov/portal for the DC trip and the conference rates for recent meetings. The cost for airfare, $2,660, is based on recent trips.

Consultant: Prof. Joseph C. Campbell, Lucien Carr Professor Electrical and Computer Engineering at the University of Virginia

Prof. Joe Campbell is a U.S. citizen and will serve as a consultant on the Phase-1 effort. He will provide comments and suggestions on issues and surface physics needed to optimize the collection of deep ultraviolet light (170 nm) in our SSPM devices. He will provide 36 hours of effort at his standard rate of $125 per hour, which is equivalent to, or better than, the rate for recent equivalent work.

Subcontract with the University of Virginia

The University of Virginia will provide a graduate student to assist in developing avalanche photodiodes that operate in the deep ultraviolet. The support for the graduate student will amount to a budget of $20,350.07 for the subcontract. The following summarizes the cost breakdown for the University of Virginia subcontract.

Low-Noise Solid-State Photomultiplier for Dark Matter Searches

	Period 1	Total
	01/15/2013	
	11/15/2013	
Graduate Student	3,835.64	3,835.64
Salary increase allowance	111.75	111.75
CY effort	20.00%	
Subtotal Personnel	3,947.39	3,947.39
Subtotal Benefits	000.00	000.00
Materials and Supplies		
Consumables	5,000.00	5,000.00
Other Costs		
GRA Tuition - no indirect costs	3,451.00	3,451.00
GRA Health Insurance	481.40	481.40
Total Direct Costs	12,879.79	12,879.79
F & A (Indirect) Costs - Modified Total Direct	7,470.28	7,470.28
Total	20,350.07	20,350.07

Subcontract with Brown University

Prof. R. Gaitskell in the Physics Department at Brown University is engaged in the development of detectors for dark matter research. He will guide the activities of a graduate student, J. Chapman, that will support for the development of SSPM devices for detecting the deep UV light emitted by liquid Xenon detectors. For their support, Brown University will require $17,850, and the following summarizes the cost breakdown for Brown University.

Salary

PI: R. Gaitskell - .5 summer mo effort - no salary

33% of 1 Graduate Student - J. Chapman		
Summer (June - August 2013)		2,365
Academic Year (Feb-May; Sept-Novem, 2013)		5,613
subtotal		7,978
Benefits		
Graduate (eff 6/2013 7.9%; eff 7/1/2013 8%)	Summer	188
Total Benefits		188
Tuition and health fees		
tuition for February - May 2013		1,570
tuition for September - November 2013		1,230
health fee for February - May 2013		100
health fee for September - November 2013		78
Total tution & health fees		2,978
Supplies Research		1,000
Total Direct Cost		12,144
MTDC (direct cost less tuition & equip)		9,166
F&A @ 62% (thru 6/2013) 62.5% (eff 7/2013)		5,706
Total Costs		17,850

Radiation Monitoring Devices, Inc. SBIR Phase II Awards

Contract Number	Funding Agency	Project Title	Type of Award	Year of Award	Total Amount of Award	Sales/Service/ License Revenue	Follow-On Funding	Subsequent 3rd Party Investment
50-DKNB-7-90143	DARPA	High Resolution Semiconductor Gamma Ray Detectors for Radionuclide Metrology	SBIR	1997	$200,000.00	$0.00	$0.00	$0.00
HSHQDC-12-C-00012	DHS DNDO	Hand-held Neutron Detector	SBIR	2012	$999,994.00	$0.00	$0.00	$0.00
HSHQDC-11-C-00033	DHS-DNDO	New Scintillator for Neutron Detection	SBIR	2011	$999,997.00	$0.00	$0.00	$0.00
HSHQDC-11-C-00061	DHS-DNDO	New Wide Bandgap Semiconductor Materials for Neutron Detection	SBIR	2011	$999,998.00	$0.00	$0.00	$0.00
HSHQDC-12-C-00016	DHS-DNDO	Eu2 Doped CsBaI3 and CsBaI3 Scintillators	SBIR	2012	$999,995.00	$0.00	$0.00	$0.00
HDTRA 1-07-C-0045	DOD	Low-Cost Individual Digital Dosimeter using Solid-state Photomultipliers	SBIR	2007	$749,999.00	$0.00	$548,500.00	$0.00
M67854-09-C-6505	DOD	Augmented Reality System (ARMS) for Complex Military Assets	SBIR	2009	$1,146,067.00	$0.00	$0.00	$0.00
F3361586-C-4527	DOD-AF	All Solid-State Integrating Dosimeter	SBIR	1987	$494,860.00	$0.00	$185,000.00	$0.00
F19628-93-C-0089	DOD-AF	Bragg Filters Using High-Scattering Efficient Volume Holographic Glass	SBIR	1993	$572,446.00	$0.00	$0.00	$0.00
DAAH01-95-C-R188	DOD-AF	High Resolution X-Ray Imaging Sensor for Real-time, Non-Destructive Evaluation	SBIR	1995	$740,000.00	$152,000.00	$0.00	$0.00
FA9101-04-C-0003	DOD-AF	Ultra Fast X-ray Imaging Detector	SBIR	2003	$749,000.00	$0.00	$0.00	$0.00
FA9101-08-C-0005	DOD-AF	Modular High Precision Digital System for Hypervelocity Projectile Measurements	SBIR	2008	$749,987.00	$0.00	$0.00	$0.00
FA8117-12C-0017	DOD-AF	Flexible, Compatible, Solid-State Eddy Current Probe for Detection of Defects Near Edges of Curved Components	SBIR	2012	$749,992.39	$0.00	$0.00	$0.00
DAAG-46-85-C-0047	DOD-ARMY	Rapid Non-Destructive Determination of Resin/Fiber Content in Composites	SBIR	1985	$599,924.00	$0.00	$0.00	$0.00
DAAL-04-87-C-0015	DOD-ARMY	Rapid Nondestructive Determination of Resin/Fiberglass Content	SBIR	1987	$390,595.00	$2,000,000.00	$0.00	$400,000.00
DAAD-07-88C-0031	DOD-ARMY	Energy Compensated, Solid-State Gamma Sensor	SBIR	1988	$509,069.00	$230,000.00	$0.00	$0.00
DASG-60-98-C-0095	DOD-ARMY	Low Cost Avalanche Photodiodes and Photodiode Arrays	SBIR	1998	$750,000.00	$65,700.00	$500,000.00	$211,000.00
DAAE 30-02-C-1014	DOD-ARMY	CZT Arrays for Ultra-Fast X-ray Imaging	SBIR	2001	$730,000.00	$747,619.00	$0.00	$750,000.00
DAAD 13-01-C-0010	DOD-ARMY	Low-Cost Microfabrication-based Biodetectors, Integrating Micro-APD Detector	SBIR	2001	$730,000.00	$1,000,000.00	$1,449,000.00	$253,000.00
N00173-00-C-2028	DOD-BMDO	New Imaging X-ray Sensor Technology for Room Temperature Nondestructive Testing	SBIR	2000	$749,999.00	$579,000.00	$0.00	$665,000.00
HDTRA 1-07-C-0044	DOD-DTRA	High Resolution, Room Temperature Semiconductor Detectors	SBIR	2007	$749,999.00	$0.00	$0.00	$0.00
HDTRA 1-08-C-0080	DOD-DTRA	Improvements in Scintillation Technology for Detection of Nuclear Radiation	SBIR	2008	$749,989.28	$0.00	$0.00	$0.00
HDTRA1-10-C-0073	DOD-DTRA	(A Novel) Cost Effective Method for Growing High Performance Radiation Sensors	SBIR	2010	$749,962.00	$0.00	$0.00	$0.00

HDTRA1-12-C-0091	DOD-DTRA	Enhanced Beta Batteries: A Long Life Power Source for Sensors Monitoring WMD Materials	SBIR	2012	$999,989.00	$0.00	$0.00	$0.00
M67854-08-C-6537	DOD-MARINES	Damage Characterization Assessment of Circuit Cards through Magnetic Automatic Test Equipment	SBIR	2008	$1,499,997.00	$0.00	$0.00	$0.00
N00039-85C-0504	DOD-NAVY	Personal Digital Neutron Dosimeter	SBIR	1985	$400,000.00	$0.00	$0.00	$0.00
M67854-05-C-6500	DOD-NAVY	Microscopic Damage Detection and Remaining Life Assessment of Printed Circuit Boards	SBIR	2004	$600,000.00	$40,000.00	$0.00	$0.00
N00421-04-C-0066	DOD-NAVY	Portable Hand-held Inspection System for Aircraft Components	SBIR	2004	$749,999.99	$0.00	$0.00	$0.00
N68335-06-C-0243	DOD-NAVY	Nondestructive Inspection (NDI) of Small-Diameter Titanium Tubing	SBIR	2006	$750,000.00	$25,000.00	$0.00	$0.00
DE-AC02-83ER80021	DOE	Advanced Avalanche Photodiode for Positron Emission Tomography	SBIR	1984	$500,000.00	$588,000.00	$0.00	$21,870,000.00
DE-FG01-85ER-80324	DOE	Indium Phosphide Neutrino Detector	SBIR	1986	$249,985.00	$4,000.00	$0.00	$0.00
DE-AC01-89ER81083	DOE	Position Sensitive Neutron Detector Using Boron Phosphide Semiconductor Sensors	SBIR	1990	$500,000.00	$25,000.00	$0.00	$250,000.00
DE-FG01-90ER81044	DOE	Thallium BromoIodide Detectors for Scintillation Spectrometers	SBIR	1990	$500,000.00	$100,000.00	$100,000.00	$350,000.00
DE-FG02-90ER-80978	DOE	A New Semiconductor Photosensor for Scintillation Spectroscopy	SBIR	1991	$500,000.00	$0.00	$0.00	$0.00
DE-FG02-93ER81530	DOE	An Integrated Video and Gamma Ray Imaging System for Robots	SBIR	1994	$600,000.00	$2,044,000.00	$1,450,000.00	$400,000.00
DE-FG02-95ER82060	DOE	A Sensor for Automated Plastic Sorting	SBIR	1996	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-95ER82061	DOE	Novel Avalanche Photodiode Arrays for UV Light Detection	SBIR	1996	$750,000.00	$197,200.00	$0.00	$335,000.00
DE-FG02-96ER82265	DOE	High Performance Optical Detectors for Calorimetry	SBIR	1997	$750,000.00	$0.00	$0.00	$45,000.00
DE-FG02-98ER82650	DOE	Large Area, Low Cost APDs Using Planar Processing	SBIR	1999	$750,000.00	$1,155,000.00	$0.00	$125,000.00
DE-FG02-99ER82866	DOE	An Advanced APD-based Spectroscopic Radiation Imager	SBIR	2000	$750,000.00	$76,000.00	$0.00	$0.00
DE-FG02-00ER83086	DOE	Linear APD Detector for Gated Spectroscopy with Single Photon Sensitivity	SBIR	2001	$750,000.00	$344,000.00	$850,000.00	$0.00
DE-FG02-00ER83084	DOE	A Fast, High Light Ouput Scintillator for Gamma Ray and Neutron Detection (GE=PI, KS)	SBIR	2001	$750,000.00	$1,462,000.00	$0.00	$0.00
DE-FG02-00ER83085	DOE	Novel APD Arrays for Scintillating Fiber Readout	SBIR	2001	$750,000.00	$30,000.00	$0.00	$0.00
DE-SC0004365	DOE	Growth of Semiconductors for Room Temperature Gamma-Ray Detection	SBIR	2001	$999,998.00	$0.00	$0.00	$0.00
DE-FGO2-01ER83269	DOE	Novel Position Sensitive Detector for Nuclear Radiation	SBIR	2002	$750,000.00	$45,000.00	$0.00	$0.00

DE-FG02-01ER83273	DOE	High Sensitivity Beta Imaging System for Surface Assessment	SBIR	2002	$750,000.00	$171,119.00	$0.00	$0.00
DE-FG02-01ER83275	DOE	High Resolution, Low Cost Small Animal PET Imager	SBIR	2002	$750,000.00	$244,000.00	$1,750,000.00	$0.00
DE-FG02-02ER83444	DOE	A New Scintillator for Gamma Ray Spectroscopy	SBIR	2003	$750,000.00	$2,105,500.00	$0.00	$0.00
DE-FG02-02ER83446	DOE	High Resolution Gamma Ray Spectrometer for Nuclear Non-proliferation	SBIR	2003	$750,000.00	$255,500.00	$0.00	$0.00
DE-FG02-03ER83758	DOE	A Novel Design for CZT Gamma Ray Spectrometers	SBIR	2004	$750,000.00	$238,000.00	$850,000.00	$0.00
DE-FG02-03ER83761	DOE	High Performance PET Detector	SBIR	2004	$750,000.00	$44,000.00	$0.00	$0.00
DE-FG02-03ER83763	DOE	Very Large, High Gain APDs for Particle Physics	SBIR	2004	$750,000.00	$44,000.00	$0.00	$0.00
DE-FG02-03ER83759	DOE	A New N+ Contact for Germanium Strip Detectors	SBIR	2004	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-03ER83760	DOE	Fast, High Resolution PET Detector	SBIR	2004	$750,000.00	$244,000.00	$0.00	$0.00
DE-FG02-03ER83762	DOE	A Design of a New Readout Sensor for SPECT	SBIR	2004	$750,000.00	$139,500.00	$0.00	$0.00
DE-FG02-04ER83898	DOE	A New Ceramic Scintillator for Neutron Detection	SBIR	2005	$750,000.00	$0.00	$1,550,000.00	$0.00
DE-FG02-04ER84054	DOE	Fast Microcolumnar Scintillator for Radionuclide Imaging	SBIR	2005	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-04ER84055	DOE	High Performance Small Animal SPECT Imager	SBIR	2005	$700,000.00	$0.00	$0.00	$0.00
DE-FG02-04ER84052	DOE	Novel Scintillator for Nuclear Physics Studies	SBIR	2005	$700,000.00	$0.00	$0.00	$0.00
DE-FG02-04ER84057	DOE	Novel Scintillator for PET Imaging	SBIR	2005	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-05ER84160	DOE	Fast, Dense Low Cost Scintillator for Nuclear Physics	SBIR	2006	$750,000.00	$0.00	$1,813,000.00	$0.00
DE-FG02-05ER84299	DOE	A New Scintillator for Time of Flight PET	SBIR	2006	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-05ER84161	DOE	High Resolution Gamma Ray Spectrometer for Nuclear Physics	SBIR	2006	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-06ER84404	DOE	High Resolution, High-Count Rate Silicon X-Ray Detector	SBIR	2007	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-06ER84402	DOE	Sensitive High Speed Detector for Synchrotron Applications	SBIR	2007	$749,999.00	$0.00	$0.00	$0.00
DE-FG02-06ER84430	DOE	An Efficient Solid State Detector for Nuclear Medicine	SBIR	2007	$750,000.00	$0.00	$0.00	$0.00
	DOE	Novel, Needle-Shaped Scintillator for Emission Transmission Tomography	SBIR	2007	$749,996.00	$0.00	$0.00	$0.00
DE-FG02-06ER84403	DOE	Fast Neutron Imaging Scintillator with Low Sensitivity to Gamma Radiation	SBIR	2007	$749,999.00	$0.00	$2,170,000.00	$0.00
DE-FG02-06ER84589	DOE	Low-Cost SSPM-based Radiation Monitor	SBIR	2007	$749,996.00	$0.00	$2,450,000.00	$0.00
DE-FG02-06ER84640	DOE	New, Bright, High Resolution Scintillators	SBIR	2007	$750,000.00	$260,000.00	$563,000.00	$0.00
DE-FG02-06ER84504	DOE	Bright, Fast Scintillator for Nuclear Studies	SBIR	2007	$749,999.00	$275,000.00	$1,863,000.00	$0.00

DE-FG02-06ER84474	DOE	Advanced Photodetector for Dark Matter Studies	SBIR	2007	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-07ER84892	DOE	Novel Ceramic Scintillators for PET	SBIR	2008	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-07ER84764	DOE	Developing CZT for Single Element Spectrometers	SBIR	2008	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-07ER84753	DOE	New Detector for Gamma-Ray and Neutron Studies	SBIR	2008	$750,000.00	$0.00	$2,600,000.00	$0.00
DE-FG02-07ER84886	DOE	High Performance X-Ray Detector Arrays	SBIR	2008	$750,000.00	$0.00	$0.00	$0.00
DE-FG07ER84903	DOE	Novel Parallax Free Sensor for Molecular Imaging	SBIR	2008	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-07ER84752	DOE	SSPM Detector for Polarized Target Scintillator Readout	SBIR	2008	$749,996.00	$0.00	$0.00	$0.00
DE-FG02-07ER84904	DOE	A Novel Microfluidic Detector with Position Sensitivity	SBIR	2008	$750,000.00	$0.00	$0.00	$0.00
DE-FG02-08ER85177	DOE	Advanced Detectors for PET	SBIR	2009	$749,994.00	$0.00	$0.00	$0.00
DE-FG02-08ER85104	DOE	New Approach for Lanthanide Halide Crystal Growth	SBIR	2009	$749,994.00	$0.00	$0.00	$0.00
DE-FG02-08ER85176	DOE	High Resolution Scintillators for SPECT	SBIR	2009	$749,991.00	$0.00	$0.00	$0.00
DE-FG02-08ER84988	DOE	Fast, Low Noise Photodetectors for Nuclear Physics	SBIR	2009	$749,994.00	$0.00	$0.00	$0.00
DE-FG02-08ER85158	DOE	Novel Approach for Depth-of-Interaction Encoding in PET	SBIR	2009	$749,995.00	$0.00	$0.00	$0.00
DE-FG02-08ER85019	DOE	Advanced Scintillation Detector for Synchrotron Facilities	SBIR	2009	$749,999.00	$750,000.00	$0.00	$0.00
DE-FG02-08ER84977	DOE	Optical Detector with Integrated ADC for Digital Readout	SBIR	2009	$749,998.00	$0.00	$0.00	$0.00
DE-FG02-08ER84999	DOE	High Performance Neutron Detector	SBIR	2009	$749,996.00	$0.00	$0.00	$0.00
DE-SC0000955	DOE	Fast, Photon Counting Detector Arrays with Internal Gain	SBIR	2010	$999,998.00	$0.00	$0.00	$0.00
DE-SC0000934	DOE	Dual Modality Small Animal Imaging	SBIR	2010	$749,998.00	$0.00	$0.00	$0.00
DE-SC0000933	DOE	New Detectors for Small Animal SPECT	SBIR	2010	$749,998.00	$0.00	$0.00	$0.00
DE-SC0000954	DOE	Low Cost, High Speed, High Sensitivity Detector for Material Science Studies	SBIR	2010	$977,448.00	$0.00	$0.00	$0.00
DE-SC0000956	DOE	Bright Quantum Dot Scintillator for High Frame Rate Imaging	SBIR	2010	$999,974.00	$0.00	$0.00	$0.00
DE-SC0000958	DOE	High Bandwidth Optical Detector for Scanning Probe Microscopy	SBIR	2010	$996,322.00	$0.00	$0.00	$0.00
DE-SC0000950	DOE	Next Generation SPECT Detectors	SBIR	2010	$749,998.00	$0.00	$0.00	$0.00
DE-SC0004535	DOE	Novel Polycrystalline Scintillators for Nuclear Non-Proliferation	SBIR	2011	$999,998.00	$0.00	$0.00	$0.00
DE-SC0004367	DOE	Novel Concept in PET Imaging	SBIR	2011	$999,998.00	$0.00	$0.00	$0.00
DE-SC0004348	DOE	New High Resolution, Large Area Detector for Synchrotron Applications	SBIR	2011	$999,998.00	$0.00	$0.00	$0.00

DE-SC0004175	DOE	Solid-State Sensor to Directly Replace Coils for Improved Eddy Current Testing (ECT)	SBIR	2011	$999,998.00	$0.00	$0.00	$0.00
DESC0006332	DOE	Non-Contact, High Speed Inspection of Zirconium Power Plant Components	SBIR	2012	$149,963.00	$0.00	$0.00	$0.00
NBCHC070018	HSARPA	Improved Spectroscopic Gamma Ray Detectors	SBIR	2007	$749,999.00	$0.00	$2,797,000.00	$0.00
HSHQDC-08-C-00057	HSARPA	High Quantum Efficiency Fast Detectors for the Readout of Scintillators for Gamma-Ray Detection	SBIR	2008	$993,316.45	$0.00	$0.00	$0.00
HSHQDC-08-C-00169	HSARPA	Improved Solid-State Neutron Detector	SBIR	2008	$999,298.00	$0.00	$3,485,000.00	$0.00
HSHQDC-08-C-00129	HSARPA	New Neutron Detectors with Pulse Shape Discrimination	SBIR	2008	$999,998.00	$0.00	$0.00	$0.00
HSHQDC-09-C-00092	HSARPA	CVD Diamond for Fission Neutron Detection	SBIR	2009	$999,597.75	$0.00	$0.00	$0.00
N10PC20052	HSARPA	Generation of Bivalent Aptamers with High Affinity and Selectivity for Detection of Viruses and Bacteria from Environmental Samples	SBIR	2010	$749,945.00	$0.00	$0.00	$0.00
NAS9-17303	NASA	Cardiac Ejection Fraction Monitor	SBIR	1985	$492,000.00	$26,600,000.00	$0.00	$4,500,000.00
NAS7-931	NASA	Soft X-ray Window Encap. For Mercury(II)Iodide	SBIR	1985	$237,436.00	$820,000.00	$0.00	$0.00
NAS7-1032	NASA	Portable Proximity Sensor for Space-Based Robots	SBIR	1988	$500,000.00	$500,000.00	$0.00	$0.00
NAS9-18515	NASA	Solid-State Neutron Dosimeter for Space Applications	SBIR	1991	$500,000.00	$0.00	$0.00	$0.00
NAS1-19309	NASA	High Field, High Tc Superconducting Magnets	SBIR	1991	$499,975.00	$0.00	$0.00	$1,000,000.00
NAS5-32518	NASA	Photodiode Scintillation Detector for Anti-Coincidence Shielding	SBIR	1993	$499,715.00	$170,000.00	$0.00	$0.00
NAS5-00229	NASA	Comprehensive Hard X-ray/Soft Gamma Ray Imaging System Using APD Array	SBIR	2001	$599,999.00	$0.00	$0.00	$0.00
NNG04CA26C	NASA	All-Digital, CMOS-Based Photodiode Camera	SBIR	2003	$599,971.00	$0.00	$0.00	$0.00
NNG04CA27C	NASA	High Gain, Position Sensitive APD for Optical Communication	SBIR	2003	$599,979.00	$0.00	$0.00	$0.00
NNJ07JA11C	NASA	Microfluidic Cytometer for Complete Blood Count Analysis	SBIR	2006	$599,965.00	$0.00	$2,100,000.00	$0.00
NNA07BA45C	NASA	Single Molecule Instrument for Surface Enhanced Raman Optical Activity of Biomolecules	SBIR	2006	$599,992.00	$0.00	$0.00	$0.00
NNJ08JA55C	NASA	Tissue-Equivalent Radiation Dosimeter-on-a-Chip	SBIR	2008	$599,951.00	$0.00	$375,000.00	$0.00
NNX11CA24C	NASA	Fast Neutron Dosimeter for the Space Environment	SBIR	2011	$599,993.00	$0.00	$0.00	$0.00

NNX12CA83C	NASA	High Resolution Detector for AT Wavelength Metrology of X-ray Optics	SBIR	2012	$749,956.00	$0.00	$0.00	$0.00
NAS3-02187	NASA GLENN	Surface Enhanced Silicon APDs for Near-IR Detection	SBIR	2002	$599,999.53	$0.00	$0.00	$0.00
NAS3-02088	NASA-JPL	A Photon-Counting Spectrometer for Elemental Analysis Using LIBS	SBIR	2002	$600,000.00	$0.00	$0.00	$0.00
2-R44-RR02568-02	NIH	Crystal Identification Sensor for PET	SBIR	1984	$241,633.00	$100,000.00	$0.00	$0.00
2-R44-GM33603-02	NIH	Improved Gel Electrophoresis System	SBIR	1985	$250,000.00	$0.00	$0.00	$0.00
2-R44-GM35057-02	NIH	Solid-State Detector for Tritium for Labeled Sample Measurements	SBIR	1986	$239,518.00	$13,000.00	$120,000.00	$0.00
2-R44-M36223-02	NIH	Sensitive Probe for Intra-Operative Bone Scanning	SBIR	1986	$259,707.00	$23,700,000.00	$0.00	$1,000,000.00
2-R44-CM-67807	NIH	Semiconductor Exposure Controller for Mammography	SBIR	1986	$226,791.00	$8,000.00	$0.00	$20,000.00
2-R44-CM-7784-2	NIH	Computer Cont. Multi-Leaf Collimator for Radiation Treatment Acceleration	SBIR	1987	$497,556.00	$0.00	$0.00	$0.00
2-R44-HL32370-02A1	NIH	Ventricular Function Monitor for Active Patients	SBIR	1987	$246,916.00	$5,600,000.00	$0.00	$1,500,000.00
2-R44-HL38561-03	NIH	Intraoperative Regional Myocardial Blood Flow Monitor	SBIR	1988	$254,629.00	$350,000.00	$0.00	$0.00
2-R44-DK39924-02	NIH	Renal Blood Flow Monitor for ICU Patients	SBIR	1989	$500,000.00	$1,000,000.00	$0.00	$300,000.00
2-R44-GM40803-02	NIH	Real-Time Imaging System for Screening DNA Libraries	SBIR	1989	$500,000.00	$0.00	$0.00	$0.00
2-R44-GM42247-02	NIH	New High Z Semiconductor for PET	SBIR	1990	$500,000.00	$0.00	$0.00	$0.00
2-R44-CM07601-02	NIH	High Con., Real-Time Portal Scanner for Radiation Therapy	SBIR	1990	$500,000.00	$0.00	$0.00	$0.00
2-R44-CA52370-02	NIH	Introperative Imaging Probe for Delineation of Tumors	SBIR	1991	$500,000.00	$136,500,000.00	$0.00	$1,600,000.00
2-R44-DK-12262	NIH	Solid-State Detector for Capillary Electrophoresis	SBIR	1991	$500,000.00	$350,000.00	$0.00	$0.00
2-R44-CA52339-02	NIH	High Sensitivity Photoconductor for Xeroradiography	SBIR	1992	$500,000.00	$25,000.00	$0.00	$0.00
2-R44-NS28955-02A1	NIH	Emboli Monitor to Reduce Surgical Neurological Deficits	SBIR	1992	$500,000.00	$25,500,000.00	$0.00	$470,000.00
2-R44-DK42385-02A1	NIH	Rapid Monitoring of the GFR of patients in the ICU	SBIR	1992	$500,000.00	$0.00	$0.00	$0.00
2-R44-CA53082-02	NIH	New Photosensor for Positron Emission Tomography	SBIR	1992	$500,000.00	$0.00	$0.00	$0.00
2-R44-HG00438-02	NIH	Large-Area Imaging Systems for Radioactive DNA Samples	SBIR	1993	$500,000.00	$0.00	$0.00	$0.00
2-R44-CA57081-02	NIH	High Resolution Digital Mammography Using CCDs	SBIR	1993	$650,000.00	$140,000.00	$1,230,000.00	$6,800,000.00
2-R44-RR07524-02	NIH	A Low Capacitance Silicon Photosensor for PET	SBIR	1993	$500,000.00	$0.00	$0.00	$0.00

Radiation Monitoring Devices, Inc. SBIR Phase II Awards

2-R44-ES05688-02	NIH	A New Portable XRF System for Lead Paint Analysis	SBIR	1993	$499,997.00	$96,343,990.00	$839,000.00	$3,500,000.00
2-R44-MH53688-02	NIH	A New Fast High Z Scintillator for PET	SBIR	1994	$535,000.00	$0.00	$0.00	$0.00
2-R44-DE10689-02	NIH	A Novel Sensor for High Resolution Intraoral Imaging	SBIR	1995	$750,000.00	$100,000.00	$0.00	$250,000.00
2-R44-CA63857-02	NIH	An Improved Image Quality Film Cassette for Mammography	SBIR	1995	$750,000.00	$15,000.00	$0.00	$0.00
2-R44-NS35698-02	NIH	InI Room Temperature Photosensors for PET	SBIR	1996	$750,000.00	$0.00	$0.00	$0.00
2-R44-RR09224-02	NIH	High Resolution Sensor for Structural Biology	SBIR	1996	$750,000.00	$0.00	$0.00	$0.00
2-R44-MH53694-02	NIH	Large Area Imaging System for Tritiated Biological Samples	SBIR	1996	$750,000.00	$0.00	$0.00	$0.00
2-R44-CA65213-02	NIH	Large Area Digital Imaging System for Mammography	SBIR	1996	$750,000.00	$0.00	$0.00	$0.00
2-R44-HL56533-02	NIH	New Germanium Detectors for Lung Burden Screening	SBIR	1997	$750,000.00	$0.00	$0.00	$500,000.00
2-R44-RR09859-02A1	NIH	CdTe Detectors for Simultaneous Emission/Transmission CT	SBIR	1997	$750,000.00	$10,000.00	$0.00	$0.00
2-R44-ES-82001	NIH	Solid-State Detector for Gas Chromatography	SBIR	1998	$750,000.00	$0.00	$0.00	$0.00
2 R44 CA 78100-02	NIH	Compact PET System for Breast Cancer Imaging	SBIR	1999	$753,118.00	$0.00	$0.00	$0.00
2-R44-CA76758-02	NIH	Scintillator for High Resolution Mammography	SBIR	1999	$754,690.00	$569,000.00	$850,000.00	$0.00
2-R44-AR44775-02	NIH	Novel X-ray Diffraction Detector for Synchotron Sources	SBIR	1999	$750,000.00	$20,000.00	$0.00	$0.00
2-R44-RR11767-02	NIH	Low Cost APD Gamma Camera	SBIR	1999	$748,623.00	$0.00	$0.00	$0.00
N44-NS-0-2306	NIH	High Performance, Two-Dimension Detector for Digital Computed Tomography	SBIR	2000	$374,575.00	$0.00	$0.00	$0.00
N44-NS-0-2305	NIH	Combined SPECT and CT System for HIV Asscociated Neuroimaging	SBIR	2000	$750,000.00	$0.00	$0.00	$750,000.00
2-R44-RR13242-02	NIH	Novel Neutron Sensor for Macromolecular Crystallography	SBIR	2000	$750,000.00	$0.00	$0.00	$0.00
2 R44 DE12785-02A1	NIH	Optical Ceramic Scintillators for Digital Radiography	SBIR	2000	$150,000.00	$0.00	$1,267,000.00	$250,000.00
2 R44 DC04138-02	NIH	Low Power, High Sensitivity Electronic Olfactory Sensors	SBIR	2001	$750,000.00	$0.00	$0.00	$0.00
2 R44 GM57746-03	NIH	Novel Silicon Detectors for EXAFS Studies	SBIR	2001	$746,721.00	$0.00	$0.00	$0.00
5 R44 HL69677-02	NIH	Large Volume CdZnTe Detectors for Nuclear Imaging	SBIR	2001	$750,000.00	$0.00	$0.00	$0.00
2 R44 RR13523-02A1	NIH	Advanced Scintillator Structure for X-ray Microtomography - PI Vivek	SBIR	2001	$749,971.00	$489,000.00	$850,000.00	$0.00
9 R44 EB00132-03	NIH	New Fast High Resolution Scintillator for PET and CT	SBIR	2002	$750,000.00	$0.00	$0.00	$0.00

2 R44 RR15992-02	NIH	High Performance Detector for Small Animal PET	SBIR	2002	$750,000.00	$0.00	$0.00	$0.00
2 R44 CA84912-02	NIH	Hybrid APD/ASIC Detector Module for Small Animal PET	SBIR	2002	$743,718.00	$0.00	$0.00	$0.00
1 R44 CA083410-02A1	NIH	Intraoperative Digital Imaging Probe	SBIR	2003	$751,590.00	$0.00	$0.00	$0.00
1 R43 CA000929-02	NIH	LSO Ceramics: A New Scintillator for Medical Radiography	SBIR	2003	$249,798.00	$0.00	$0.00	$0.00
5 R44 EB001924-03	NIH	High Resolution, High Sensitivity PET Imaging of Small Animals	SBIR	2003	$923,197.00	$0.00	$0.00	$0.00
2 R44 RR017126-02	NIH	Bandwidth-Selective, APD-Based Flow Cytometer	SBIR	2004	$894,653.00	$0.00	$0.00	$0.00
2 R44 CA091420-03	NIH	High Resolution Imaging Detector for Mammography	SBIR	2004	$1,050,000.00	$0.00	$0.00	$0.00
9 R44 EB003382-03	NIH	Reduced Afterglow CsI(Tl) Scintillator for Medical Applications	SBIR	2004	$521,437.00	$90,000.00	$0.00	$0.00
9 R44 HL078295-02	NIH	High Resolution, Low Cost Gamma Camera	SBIR	2004	$750,000.00	$0.00	$0.00	$0.00
2 R44 CA094385-03	NIH	High Resolution Positron Emission Mammography	SBIR	2004	$1,049,938.00	$0.00	$0.00	$0.00
2 R44 EB000477-02	NIH	A New Scintillator for Nuclear Medicine Imaging	SBIR	2004	$854,969.00	$0.00	$0.00	$0.00
4 R44 EB001686-02	NIH	High Resolution Small Animal SPECT	SBIR	2005	$1,043,920.00	$0.00	$0.00	$0.00
2 R44 EB001009-02	NIH	Optical Ceramic Hafnates: New Fast PET Scintillator	SBIR	2005	$900,007.00	$0.00	$1,100,000.00	$0.00
2 R44 CA095936-04	NIH	In Vivo Molecular Imaging of Cancer in Small Animals	SBIR	2005	$920,980.00	$0.00	$0.00	$0.00
4 R44 EB004290-02	NIH	A Fast, High Luminosity Scintillator for PET	SBIR	2005	$1,092,821.00	$0.00	$0.00	$0.00
2R44 CA101243-02A1	NIH	High Sensitivity X-ray Detector for PET/CT	SBIR	2005	$859,764.00	$0.00	$0.00	$0.00
2 R44 CA101266-02A1	NIH	Near IR Photon-Counting Camera for Diffuse Optical Tomography	SBIR	2006	$829,949.00	$0.00	$0.00	$0.00
2 R44 ES012515-02	NIH	Species-level Identification of Pathogenic Viruses on a Microfluidics Platform	SBIR	2006	$830,261.00	$0.00	$0.00	$0.00
2R44CA096030-04	NIH	Solid State Beta Imaging Sensor for Radioguided Surgery	SBIR	2006	$985,949.00	$0.00	$0.00	$0.00
2 R44 RR021257-02A1	NIH	Digital 2-D Neutron Detector for Protein Function Studies	SBIR	2007	$830,251.00	$0.00	$0.00	$0.00
5 R44 NS055377-03	NIH	High Resolution PET Detectors for Combined PET-MR Small Animal Imaging	SBIR	2007	$984,997.00	$0.00	$0.00	$0.00
5 R44 HL083494-03	NIH	High Resolution Nuclear Cardiac Imaging	SBIR	2007	$852,925.00	$0.00	$0.00	$0.00
5 R44 CA001871-03	NIH	High-Speed Micro CT Detector for Physiologic Studies	SBIR	2007	$777,227.00	$0.00	$0.00	$0.00
2R44ES012361-03A1	NIH	A New High Performance Detector for Small Animal SPECT	SBIR	2008	$962,923.00	$0.00	$0.00	$0.00
2R44CA099104-03A1	NIH	High Resolution Mammography Sensor	SBIR	2008	$977,915.00	$0.00	$0.00	$0.00
2R44CA105650-02A1	NIH	Cancer Detection Using Diffuse Luminescence Imaging	SBIR	2008	$1,080,221.00	$0.00	$0.00	$0.00

5 R44 NS060197-03	NIH	New Solid-State Photosensor for PET	SBIR	2009	$645,761.00	$0.00	$0.00	$0.00
2R44RR022463-02	NIH	High Spatial Resolution Structured Plastic Scintillator	SBIR	2009	$1,229,941.00	$0.00	$0.00	$0.00
2R44RR024272-02	NIH	Bright and Fast Sensor for Time Resolved X-Ray Diffraction Studies	SBIR	2009	$1,207,979.00	$0.00	$0.00	$0.00
2R44EB007870-02	NIH	High Performance Transparent Optical Ceramic Scintillators through Nanotechnology	SBIR	2009	$1,318,815.00	$0.00	$0.00	$0.00
2R44ES015439-02	NIH	Instrument to Identify Children's Products that Could Cause Lead Poison	SBIR	2011	$951,056.00	$0.00	$0.00	$0.00
8R44EB016093-04	NIH	Multibeam Healing for Laser Micromachining in Manufacturing	SBIR	2011	$1,592,997.00	$0.00	$0.00	$0.00
2R44EY019197-02	NIH	Near Infrared Detector for Advanced Opthalmology	SBIR	2012	$717,839.00	$0.00	$0.00	$0.00
SB34111CN0093	NIST	High Speed and High Sensitivity Quadrant Photodetector	SBIR	2012	$299,995.00	$0.00	$0.00	$0.00
DAR-7917427 (b)	NSF	Photovoltaic Detectors for High-Intensity X-ray Measurement	SBIR	1983	$212,830.00	$600,000.00	$0.00	$25,000.00
MEA-8316542	NSF	Rapid Non-Destructive Measurement of Reinforced Plastics	SBIR	1984	$199,990.00	$4,730,000.00	$0.00	$75,000.00
ISI-8716898	NSF	Lead Iodide Semiconductor Nuclear Sensors	SBIR	1988	$203,402.00	$320,000.00	$150,000.00	$4,650,000.00
ISI-8722119	NSF	Controlled Polytypism in a Variable Bandgap Semiconductor	SBIR	1988	$202,834.00	$0.00	$0.00	$0.00
ISI-8821887	NSF	Thallium Bromide Nuclear Detectors	SBIR	1989	$226,322.00	$50,000.00	$1,100,000.00	$2,700,000.00
ISI-9001042	NSF	A New Semiconductor Photosensor for Scintillation Spectroscopy	SBIR	1990	$250,000.00	$350,000.00	$0.00	$0.00
ISI-9201872	NSF	Large Area, Real-Time Imaging System for Screening DNA Libraries	SBIR	1993	$250,000.00	$0.00	$0.00	$0.00
DMI-9505294	NSF	Avalanche Photodiodes for Scintillating Fiber Detectors	SBIR	1996	$300,000.00	$0.00	$0.00	$250,000.00
DMI-9801247	NSF	A Novel Flat Panel Detector for X-ray Detection	SBIR	1998	$600,000.00	$739,000.00	$0.00	$675,000.00
DMI-9983337	NSF	Advanced Micro-Pixelized Scintillator for Structural Biology	SBIR	2000	$550,000.00	$564,000.00	$0.00	$300,000.00
DMI-0450483	NSF	Advanced Detectors for X-Ray Diagnosis	SBIR	2005	$500,000.00	$0.00	$0.00	$0.00
DMI-0450539	NSF	Detection and Identification Instrument for Single Molecule Analysis	SBIR	2005	$500,000.00	$0.00	$0.00	$0.00
OII-0522021	NSF	Gamma Ray Detector for Geophysical Examination	SBIR	2005	$479,410.00	$0.00	$0.00	$0.00

Project Summary: Low-Noise Solid-State Photomultiplier for Dark Matter Searches

Principal Investigator: Dr. Erik B. Johnson, Senior Scientist
Topic: 42. A. Advances in Detector and Spectrometer Technology

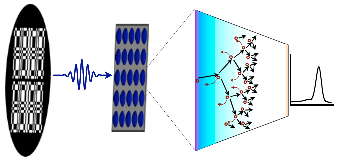
Statement of the Problem Being Addressed:
To provide the next generation of highly sensitive dark matter detectors, advanced UV sensitive photodetectors need to be developed to provide a large gain, a high detection efficiency, an insignificant dark current, and an insensitivity to extreme, cryogenic environments. Though the photomultiplier tube has served this purpose for years, the next-generation of solid-state photomultipliers will provide high-efficiency UV detection without the adverse properties of existing silicon photomultipliers or photomultiplier tubes.

Statement of How the Problem is Being Addressed:
This program will explore the development of an advanced solid-state photomultiplier using either silicon or 4H-SiC to achieve these goals. Silicon is a mature material that provides a high detection efficiency for UV photons and 4H-SiC has a high band-gap that allows for significant noise suppression. The program will exploit the advantages of the candidate materials and provide an optimized photodetector for dark matter searches. The solid-state platform for photodetection is ideal as detection efficiency can be higher, and devices are insensitive to magnetic fields or other environmental conditions, while device fabrication is done in a more cost effective manner with the possibility of integrating on-chip circuitry.

Commercial Application and Other Benefits:
Along with nuclear and high-energy physics applications for scintillator and Cherenkov readout, the proposed technology can be used for a myriad of applications, particularly in UV astronomy or for military applications such as exhaust plumes from jet engines or detection of camouflaging materials. In the scope of security and medical applications, UV detectors are used for detection and identification of biological or chemical agents, along with spectrophotometry, PET and SPECT imaging, gamma and x-ray cameras, radioluminscent assays, flow cytometry, DNA sequencers, and radiation monitors to name a few.

Key Words:
Solid-State Photomultiplier, Avalanche Photodiode, Geiger Photodiode, 4H-SiC, Silicon

Summary for Member of Congress:
In search for fundamental properties of the Universe regarding dark matter, a high-performance UV photodetector using advanced semiconductor processing techniques will be developed, which has additional applications for science research, biological and chemical agent detection, medical imaging, radiation detection, and spectroscopy to name a few.



The Instrument Research &
Development Group

Low-Noise Solid-State Photomultiplier for Dark Matter Searches

DOE Phase I SBIR Grant Application

Topic: 42
Subtopic: A
Nuclear Physics Instrumentation, Detection Systems and Techniques
Advances in Detector and Spectrometer Technology

Radiation Monitoring Devices, Inc.
44 Hunt Street
Watertown, MA 02472

Principal Investigator:
Dr. Erik B. Johnson
Senior Scientist

A. Identification of the Problem or Opportunity, and Technical Approach

Dark matter searches require the use of sensitive target materials, and as xenon is an ideal candidate, highly sensitive photodetectors are required to detect the light produced when Weakly Interacting Massive Particles (WIMPs) scatter with xenon atoms. Due to the extreme environment of the liquid xenon target and light production yields from WIMP interactions, the next generation of dark matter detectors require robust, low-noise, high efficiency photodetectors.

The photomultiplier tube (PMT) is the photon detector of choice, primarily because of its low noise performance. Careful selection of a phototube is required for dark matter searches to limit natural radioactive background and thermal stress, while providing a high quantum efficiency. For the R8778 tubes to be used in the LUX experiment, the quantum efficiency is 33% [1]. Additional limitations for PMTs include bulkiness, requirement of high voltage, sensitivity to large magnetic fields, and susceptibility to helium gas.

The alternative to the photomultiplier tube is the solid-state photomultiplier (SSPM), which has been shown to achieve single photon detection, as shown in Figure 1. As the light yield is very low for liquid xenon interactions, single photon detection is critical for the detection and study of dark matter. Single photon detection is obtained by using an array of Geiger photodiodes operated beyond their reverse bias breakdown, providing a ~10^6 gain. The signal from each diode is readout in parallel, allowing for a two terminal device [2-10].

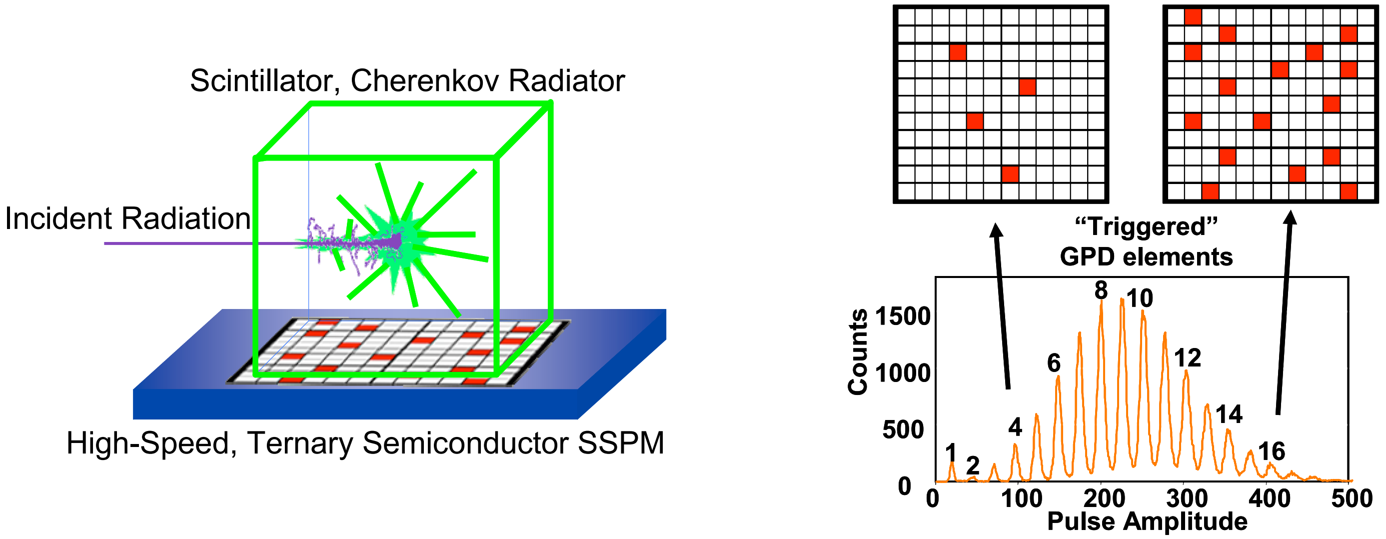


Figure 1: Diagram showing the concept of operation of an SSPM. A light pulse from ionizing radiation within a scintillator is detected by the SSPM, where the number of Geiger photodiodes triggered is proportional to the incident light intensity. The low right hand plot shows real data of an LED pulse gated with the readout of the SSPM.

SSPMs haven't supplanted the PMT primarily due to the dark current, and this program will provide a photodetector with significantly lower dark current than existing devices, while providing higher detection efficiency than a PMT. If the dark current at room temperature is less than a PMT, the SSPM has high potential to supplant the PMT in that they:

- use less material (radioactive background is suppressed),
- can achieve higher quantum efficiencies over a broader spectral range,
- use small operating bias,
- insensitive to magnetic fields or other environmental conditions,
- are fabricated in a more cost effective manner,
- can obtain a rise time similar to a PMT,

- provide an excess noise comparable to or less than a PMT, and
- allow for on-chip circuitry.

In order to achieve these improvements, a solid-state photomultiplier will be developed using a costume process that will either use 4H-SiC or silicon. The advantage of 4H-SiC is the high bandgap, which provide extremely low dark currents, but this material has not been used for photodetection down to 175 nm, the emission wavelength of xenon. Silicon with a lower bandgap will have intrinsically higher dark currents, but silicon is significantly more mature and has demonstrated high quantum efficiency, ≥ 100% [11, 12] at 175 nm due to multiple electron-hole production at these photon energies. Though both materials, silicon [12-14] and 4H-SiC [15-17] have been used for fabrication of avalanche photodiodes for UV detection, whether in Geiger mode operation or not, there has not been direct development of a Geiger photodiode, as those developed at RMD.

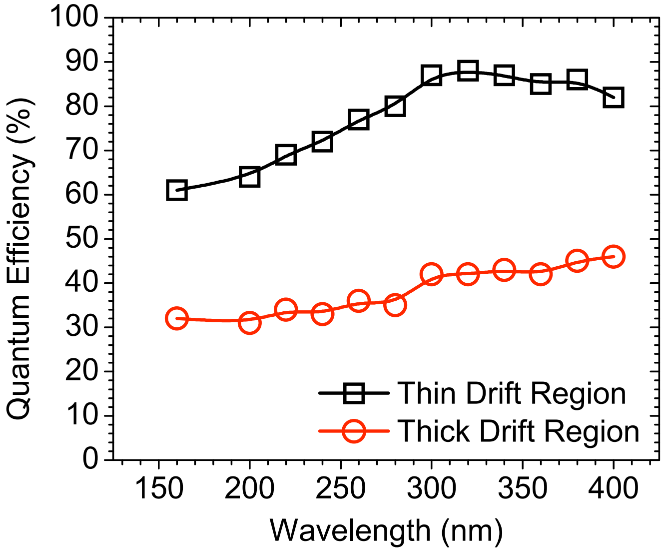


Figure 2: Plot of the QE of the RMD APD, designed with a thin or thick drift region, as a function of wavelength.

A.1. Improving Upon the Silicon Photomultiplier

Existing avalanche photodiodes (APD) developed at RMD have been designed with improved quantum efficiency. The basic design of the APD consists of a drift region influenced by low-electric field, which may lead to recombination, which decreases the quantum efficiency. When this drift region is reduced, the quantum efficiency is increased, as directly shown in Figure 2.

As shown with RMD's APDs, which are manufactured in-house, RMD has begun to migrate this feature to Geiger photodiodes (GPD) using commercial CMOS processes. The baseline design, shown in Figure 3, is constructed to provide a high electric field near the surface for charge collection, where we observed a clear improvement in the quantum efficiency, as the efficiency roughly doubled in the region from 375 to 450 nm. The structure allows for a compact diode, minimizing the volume, which will reduce the dark current. Improving the near surface charge collection and reducing the dark current is a multifaceted development process. As we explore the potential for development of a silicon GPD for dark matter searches, we will develop an in-house process that exploits the advanced design features both in our GPD and APD work for fabrication of a high-gain, low-noise photodetector.

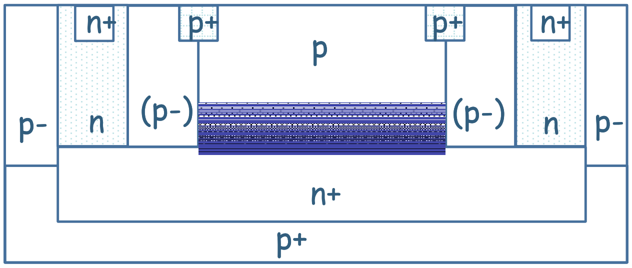


Figure 3: Diagram of the inverted p-n Geiger photodiode. The diode uses a buried n+ region and lightly doped p region to extend the electrical field up toward the surface.

Another issue with near surface charge collection is due to band pinning due to the transition from a semiconductor to an insulator, such as silicon to silicon dioxide, as illustrated in Figure 4. This causes electron or holes to be isolated near the surface, without sufficient energy to traverse into the bulk of the material where avalanche multiplication takes place. To overcome this issue, we plan to exploit our GPD design shown in Figure 3 along with near surface doping structures, which will significantly reduce the near surface band pinning, which has been demonstrated in [11, 18].

An APD developed by Prof. Campbell's group is shown in Figure 5, which uses a thin 50 nm n+ region at the top of the p-i-n [19]. The structure shows an increase in quantum efficiency at 240 nm from 18% to 50% due to the change in the diode configuration when compared to previous versions of 4H-SiC APDs. A native oxide is used for top passivation with and AlGaN window.

As indicated in Figure 6, 4H-SiC has an intrinsicly lower dark current density than silicon primarily due to the higher bandgap. The absolute dark current of a material is correlated to the recombination-generation density, electric field, doping concentration, volume of the semiconductor, and surface effects. It is suspected that the 4H-SiC might provide lower dark current, but the wafer and process quality needs to match the state-of-the-art for silicon to demonstrate the potential shown in Figure 6.

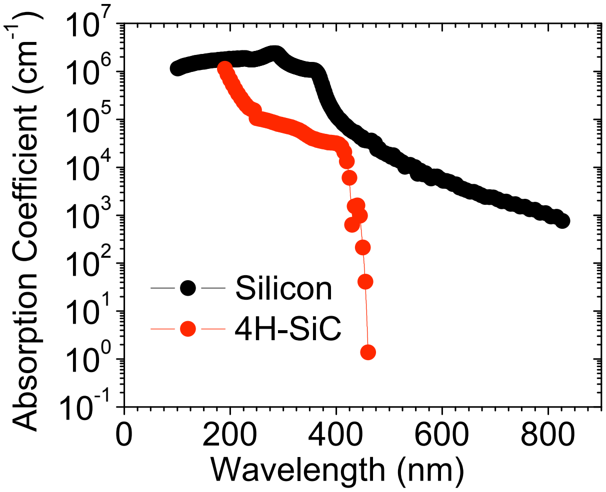


Figure 4: Plot of the attenuation coefficients for silicon and 4H-SiC as a function of wavelength. As illustrated below [19], the band pinning occurs at the silicon/passivation interface, which causing band pinning and a loss in charge collection.

High quantum efficiency from solid-state devices is possible, and when the proper material and design is used in tandem with a high-quality fabrication process, the dark current will be suppressed. Through empirical data and device simulations, the Phase-I program will demonstrate that a high-performance solid-state photomultiplier can be fabricated as a direct replacement for a photomultiplier tube, particularly for dark matter experiments.

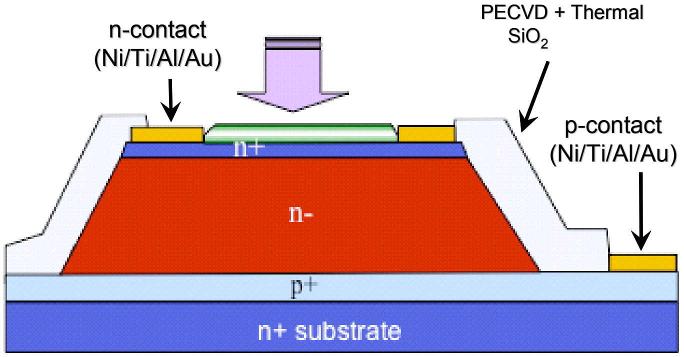


Figure 5: Illustration of the advanced 4H-SiC photodiode developed by Prof. Campbell's group, which uses a thin n+ region at the surface to minimize band pinning.

A.2. The LUX Dark Matter Experiment

The LUX dark matter experiment is located at 4850 ft below sea level at the Davis Laboratory, and consists of roughly 300 kg of liquid xenon placed within a 300 ton water tank for shielding against muons. As WIMPs being the primary candidate for dark matter within the universe, a dense, massive nucleus is needed for detection of elastic interactions with a WIMP. Aside from being able to provide a large volume, liquid xenon, having a high density in liquid phase, has many favorable properties, in that it has a massive nucleus, is inert, has no naturally occur radioisotopes that will prose a background problem, and scintillates. Liquid xenon is relatively easy to handle compared to other cryogens, and the scintillation light can be easily used to discriminate nuclear recoils from electron recoils. Other experiments, such as XENON, EXO, ZEPLIN-III have employed this material for detection of WIMPs. To discriminate against background, the liquid xenon is used within a time projection chamber configuration.

As a WIMP interacts with a xenon nucleus within the liquid volume, the recoil causes ionization of the atom, where some of the electrons recombine producing light. This initial light pulse is referred to the S1 signal seen in Figure 7. In the presence of an electric field, some of the electrons a directed toward the surface of the chamber, while the recombined electrons produce roughly 5 detected photons per keV$_{ee}$ for a phototube with a quantum efficiency of 33%, indicating that only 15 photons per keV$_{ee}$ are incident on the PMT per WIMP event, on the order of 2 keV$_{ee}$ [1]. For the remaining electrons that do not recombine and are accelerated toward the surface, they are injected into a high field region consisting of xenon gas, where addition light is produced through an electroluminescence process. Given the right conditions, it is expected that 35 photons per electron are produced per electron extracted from the liquid xenon, and from gamma induced events with energies of 10 keV$_{ee}$, it is expected that 45 electrons per keV$_{ee}$ energy deposited is expected to provide the S2 signal [1]. The light signal is distributed over multiple phototubes on the top and bottom of the chamber, providing X-Y information, while the timing between S1 and S2 provides the Z information. Based on the light response and position information, the full event kinematics is reconstructed.

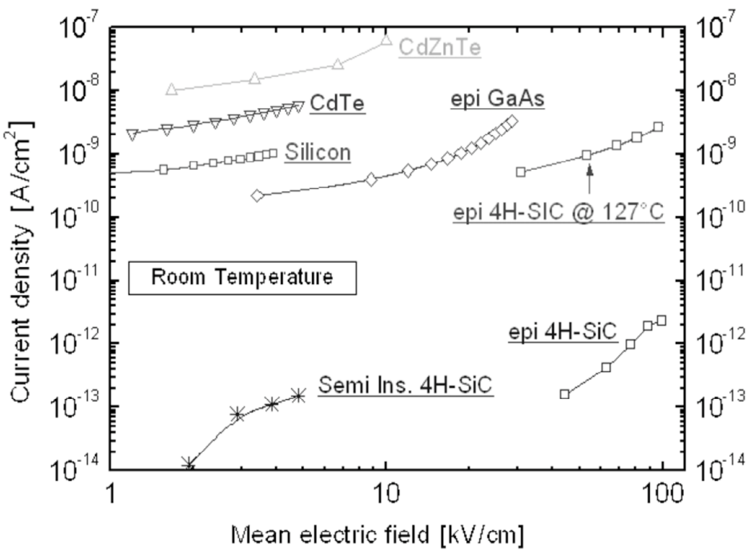


Figure 6: Room temperature dark current density of detectors fabricated using different semiconductor materials [20].

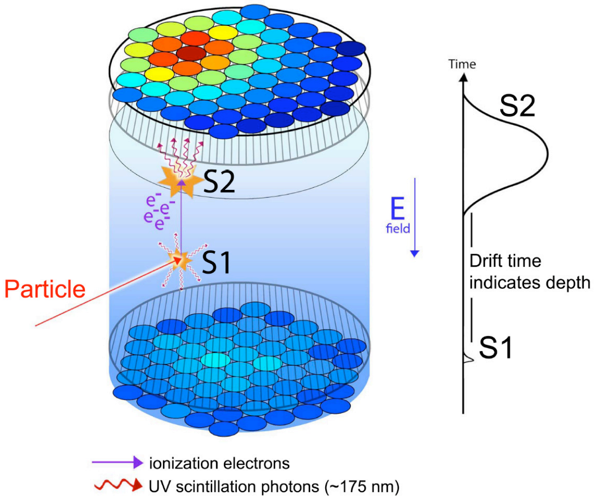


Figure 7: A diagram of the active liquid xenon chamber within the LUX experiment [1]. The S1 signal is from the recombination of freed electrons with xenon, while other freed electrons are directed by the electric field to a gas region, where the electrons induce more photons through an electroluminescence process.

B. Anticipated Public Benefits

The primary use of the instrument will be for scientific research both in nuclear and high energy physics, as the photodetector will be able to detect UV photons with efficiencies higher than the standard photomultiplier tube. UV solar-blind detectors, which can be developed with the knowledge obtained within this program, are used for a myriad of applications, particularly in UV astronomy. A UV solar-blind system utilizing this technology can be used for military applications such as detection of exhaust plumes from jet engines or camouflaging materials. The UV sensitive solid-state photomultiplier developed here will provide a detector for spectrophotometry, PET and SPECT imaging, gamma and x-ray cameras, radioluminscent assays, identification of biological or chemical agents, flow cytometry, DNA sequencers, and radiation monitors to name a few.

C. Technical Objectives

The program is designed to fabricate a UV-sensitive, high-gain, high-speed photodetector for dark matter searchers. The technical challenges of the Phase-I program is to provide the necessary background data on the potential diode structure and wafer quality for designing Geiger photodiodes on an ideal candidate epitaxial wafer. The technical objectives are:

- Demonstrate through simulations a diode structure biased in Geiger mode, with a uniform, high electric field within the bulk, while sustaining good low field termination at the device periphery to prevent edge breakdown.
- Demonstrate through simulations a diode structure with high quantum efficiency (> 33%) for photons with wavelengths from 150 nm to 250 nm.
- Provide data on wafer quality and substantiate with diode design for establishing low dark count rates.

D. Phase I Work Plan

The work plan reflects the effort to meet the technical objectives within a nine month period. The work will meet the technical objectives by conducting various simulations of Geiger photodiode (GPD) designs to identify best candidates for low noise and high detection efficiency. The work plan will also include some preliminary studies on wafer quality to validate the available wafer quality for fabrication of low-noise detectors. A summary of the work plan follows:

Task 1:	Establish Design Specifications
Task 2:	Identify Candidate Semiconductor
Task 3:	Design GPD Elements
Task 4:	Simulation of GPD Characteristics
Task 5:	Procure Materials and Process Wafer
Task 6:	Conduct Baseline Studies at Temperature
Task 7:	Measure Baseline Wafer Characteristics
Task 8:	Write Phase-I Reports and Phase-II Proposal

D.1. Task 1: Establish Design Specifications

The design specifications will be reviewed by the collaboration. These design specifications will focus on the implementation of a photodetector within a liquid xenon based time projection chamber, but the specifications will not limit the use of the photodetector for other applications. The primary specifications of noise terms and detection efficiency will be identified, but additional specifications associated with the response time of the detector will be reviewed. These later specifications will lead to additional applications relevant the nuclear physics research. As the fabrication process utilizes proven fabrication techniques within the semiconductor industry, cost effective processing methods will be considered for establishing a low-cost, high-performance detector. The primary work within this task will consist of conducing meetings with the collaboration members to review expectations and to establish requirements of the photodetector. The work will generate a document that identifies these specifications for implementation into the design.

D.2. Task 2: Identify Candidate Semiconductor

The work will focus on a trade study between silicon and 4H-SiC. Though silicon is a very mature technology, 4H-SiC is rapidly maturing as various industries are utilizing the properties of 4H-SiC for advanced integrated circuits. For the proposed application, some important photodetector material characteristics will need to be identified and compared between Si and 4H-SiC.

4H-SiC is used in high-temperature and lighting applications, and it is being developed for photodetection for a myriad of applications [21]. It is suspected that 4H-SiC may have better excess noise performance, but 4H-SiC hasn't been demonstrated to provide high detection efficiency at 170 nm. Though the 4H-SiC APDs that have been developed [22-24] and show high quantum efficiencies above 250 nm, the diode design will need to be developed for proper charge collection for photons below 250 nm. As we see from Figure 4, the absorption coefficient is approaching that of silicon at wavelengths down to 150 nm, which is a major reason why most 4H-SiC photodetectors are limited down to about 200 nm.

Silicon on the other hand is limited by the small band gap. For 170 nm light, the low band gap of silicon is beneficial and a draw back. Though it is expected that silicon will have an inherent higher dark current, the lower band gap will allow for multiple photoelectrons tube generated per incident 170 nm light.

RMD will review these candidate materials, generating tables and conducting a trade study as to what material should be used for developing a low-noise solid-state photodetector for dark matter searches. The review will generate a report, which will be discussed with Prof. Joe Campbell. The result of this task is to identify benefits of one technology over the other, as the goal of this task will not ultimately select one material.

D.3. Task 4: Design GPD Elements

RMD and Prof. Campbell will conduct meetings and generate documentation for the design of the fundamental element of the solid-state photomultiplier, the GPD. RMD will conduct the majority of the work involved in the design of the GPDs, as Prof. Campbell will provide feedback in the designs and any additional suggestions. Design considerations include: wafer growth, diode definition and structure, diode fabrication processes, annealing or gettering processes, electrical contacts, passivation processes, and surface engineering and post processing.

The diode definition and structure is a process that will be primarily identified by RMD, as the goals will be to reduce noise, provide low dark currents, and reduce side wall/peripheral electrical fields. The major goal of the design must provide a diode structure that has a high, uniform electric field within the central region of the diode with a low field on the perimeter for proper side wall termination. Good electrical contacts will need to be made, and this is a process that is different for each material. The passivation process will be a key element in the design of the photodetector primarily due to the physics associated with the very, short wavelengths involved, and proper passivation (most likely SiO_xN) is critical for minimize surface induced dark events, as well as maximizing surface charge collection.

The work conducted under this task will result in various designs that will be simulated in the follow task. A milestone will be reached at the end of this task, which is the design document of the potential Geiger photodiodes that will be simulated.

D.4. Task 4: Simulation of GPD Characteristics

Simulations on the designs will be done to determine the initial design within the scope of the material and process parameters. We will use commercial Technology Computer-Aided Design (TCAD) tools to perform most of the simulations. Recently, both Silvaco and Synopsis have successfully produced accurate simulation results on devices such as Schottky diodes and field-effect transistors [25, 26]. Using Silvaco TCAD, virtual photodiode structures (an example SiC mesa-type photodiode structure provided in Figure 8) will be built by RMD scientific staff. The simple approach is to build the devices geometrically using Silvaco's DEVEDIT. The simulations will be used to determine the potential GPD candidates.

In this task, RMD will perform the TCAD simulations, analyze the results and provide electric field profiles and charge distribution characteristics associated with the different junctions in the GPD pixel at different operating voltages. Using optoelectronic device simulators, optical characteristics

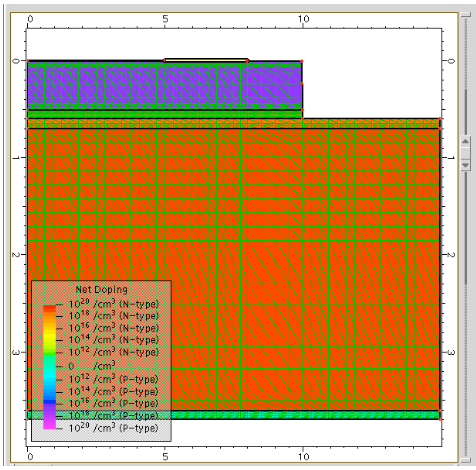


Figure 8: A 2D 4H-SiC mesa photodiode structure generated using Silvaco Inc.'s DEVEedit TCAD software.

such as responsivity may be derived. Device simulations will be performed on many design variations, including different doping concentrations and pixel geometries.

In Figure 8, a preliminary mesa type epitaxial SiC photodiode structure is generated using Silvaco tools. The photodiode structure (without surface AR coating) contains the following epitaxial layers: from the top, p+ 4H-SiC (5e19 cm^{-3}), p 4H-SiC (5e16 cm^{-3}), n 4H-SiC (2e18 cm^{-3}), n+ 4H-SiC (5e18 cm^{-3}), n+ 4H-SiC substrate (1e19 cm^{-3}). The simulated quantum efficiency of the SiC diode is shown in Figure 9. As the simulation results indicate, 4H-SiC is most sensitive to wavelengths below 450nm. At the 170nm to 190nm range, even without AR coating, the simulated QE is still remarkably high, around 60%. However, with surface defects and other process induced imperfections in the device material, the actual QE should be expected to be lower.

As Prof. Campbell has extensive experience with SiC, his research group has developed a number of Monte Carlo, empirically based models. The methods used in handling the simulation is different compared to the TCAD tools, but are based on diode designs that are significantly different than what will be developed in this program. Prof. Campbell's simulations will complement the simulation conducted by RMD, but the program will only request Prof. Campbell to simulate designs that have been previously vetted by RMD.

This task will provide simulated results on various diode designs, and a few candidate designs will be identified for potential fabrication. The process will be iterative and conducted over the majority of the program. As new information is obtained from the remaining tasks, the designs will be modified accordingly. The work will produce a conceptual design review document for the potential Geiger photodiode designs, indicating the benefits and drawbacks for each design. The review will satisfy our second milestone.

D.5. Task 5: Procure Materials and Process Wafer

Based on initial design parameters, epitaxial wafers will be purchased from any one of a number of companies, such as Cree, Dow Corning, United SiC, Topsil, El-Cat, IQE, or Landmark. RMD will conduct all of the work required to specify and purchase the material. The majority of the work in this task will be to look at the quality of 4H-SiC, as it is widely accepted that silicon devices will be of the highest possible quality due to the maturity of the technology.

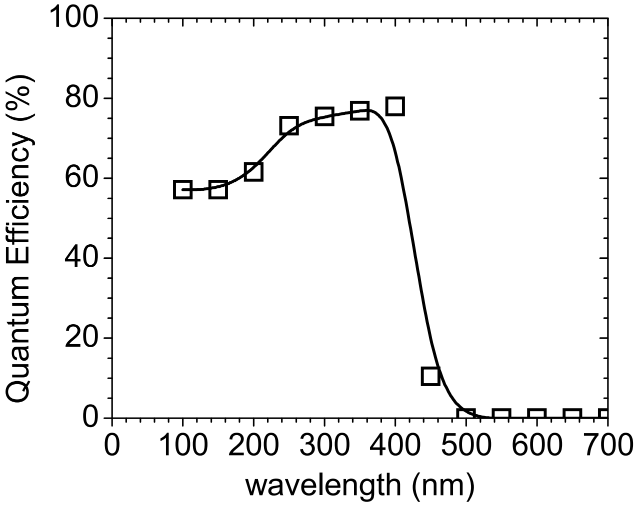


Figure 9: A simulated measure of the quantum efficiency for light incident normal to the surface of the 4H-SiC.

RMD and UVa will process 4H-SiC and silicon epi wafers and fabricate very simple designs on the wafer to assess the wafer quality. At the University of Virginia, facilities and equipments for etching (both dry and wet), diffusion, passivation, and metallization are available. At RMD, some processing steps such as wet etching, diffusion, passivation and metallization can be performed. The diode doping and junction thickness are defined by the epitaxial layers on the purchased epi-wafer, and the overall geometry of each test device will be defined by photolithography and etching.

Separate photomasks are needed for each process step such as diode definition, diffusion, etching, passivation, and metal deposition. The photomasks defines the geometrical features of the diode structural components (such as diode mesa/active area), contact ring/finger, passivation area, etc) during the fabrication process. RMD or UVa will subcontract an outside vendor such as Photo Sciences Incorporated (PSI) for all photomask fabrication.

Using simple photolithography techniques, test structures will be defined by the photomask and photoresist exposure. Mesa structures will be etched in the wafer material using simple diode geometries defined by the photomask. There are two main techniques: 1) Chemical wet etch, and 2) Dry etch (Plasma or Reactive Ion). Wet etching is difficult for SiC, due to extreme high temperature requirement (>450 C) and high concentrations of hazardous chemicals such as HF. The most reliable and widely used etching method is dry etching using either inductively coupled plasma (ICP) or reactive ion etch (RIE). ICP/RIE uses a mix of chemical and physical gas plasmas to perform etching. The technique is precise, and the etching rate and directionality can be controlled. For silicon processing, wet, dry or a combination of both etching techniques can be used. Depending on final GPD design, wet etching using solutions such as potassium hydroxide (KOH), or Tetramethylammonium hydroxide (TMAH) can be used. For insulation/passivation layer (SiO_2 or Si_3N_4) etching in SiC or silicon, buffered hydrofluoric acid (HF) and Phosphoric acid (H_3PO_4) are commonly used.

After simple diode structures are etched, appropriate surface passivation and metal contact deposition will be performed to finalize the test structures for quality evaluation. Surface passivation is used to terminate surface crystal structure, repair dangling bonds, and protect device surface. Good surface passivation will significantly reduce surface defect density and increase surface charge collection. For silicon and SiC, SiO_2 is often used for passivation, as it is a natural oxide for both silicon and SiC. Si_3N_4 is another passivation material that can be used. The final step in processing is metallization of device contacts. For good electrical behavior, the metal contacts need to be as ohmic as possible. For silicon, Al is usually used, and for SiC, a combination metal stack using Ni, Ti, Au is commonly used.

The goal of the task is to generate large area structures for wafer evaluation. The process of verifying the wafer quality will be information that is an input to the simulations. This process will not generate a Geiger photodiode, but simple photodiode structures will be generated. This task will provide processed wafers for characterizing.

D.6. Task 6: Conduct Baseline Studies at Temperature

Professor Gaitskell's group at Brown University will perform measurements on photodetectors using the experimental setup in the Brown lab. These experiments will test the stability and performance of the devices when cooled to 170K (liquid xenon temperature). The Brown group has a cryostat and pumping system for this purpose. The detectors will be placed in the cryostat with a blue LED pulsed light source. The chamber will be pumped to vacuum and backfilled with dry nitrogen as an exchange gas. The cryostat will be submersed in an ethanol bath that will be cooled with liquid nitrogen until the desired temperature is reached. The Brown lab has the ability to easily temperature cycle the devices and test for gain, single photoelectron sensitivity and noise. The Brown group will perform these measurements on existing devices (either silicon or 4H-SiC) developed at RMD and University of Virginia in order to inform the design and fabrication stages of Phase I. Though existing designs might not function at these temperatures, the loss in performance as a function of temperature provides direct information on the mode of failure. Aside of a loss in carrier density, there are other effects such as tunneling that will cause degradation in signal, and these effects are temperature dependent, particularly from room temperature down to 170 K. The performance characteristics of the existing avalanche photodiodes and Geiger photodiode as a function of temperature will be documented.

D.7. Task 7: Measure Baseline Wafer Characteristics

RMD will evaluate the quality of wafer materials using fabricated test devices. Since simple test structures contain pn junctions for both SiC and silicon epi-wafer Diode junction capacitance (CV) and current vs. voltage (IV) characteristics can be easily measured using CV meters and IV curve tracers. Steady-state CV measurement is an easy measurement to estimate deep-level defect density in the device. Using measured junction capacitance as a function of reverse bias, the deep-level defect density can be related the deep level filled trap density. CV measurements will be done using a HP4274 LCR meter.

IV measurements using a HP4145 semiconductor parameter analyzer will be performed to assess the room temperature dark current for both 4H-SiC and silicon test diode. The IV measurements does not give estimates of defect densities, but the measure of diode saturation current gives a qualitative measure of material quality in the device. Forward IV measurement on the diodes can also provide a simple measure of carrier recombination lifetime, which identifies how fast the photo-induced charges recombine in the device and a measure of charge collection efficiency.

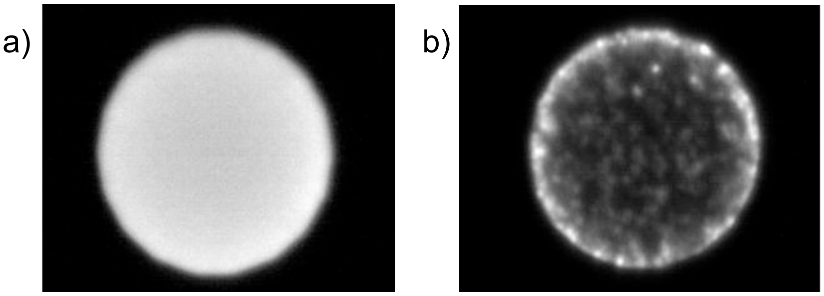


Figure 10: Emission microscopy results of the electroluminescence image of two circular silicon photodiodes from two wafers of different quality [27].

Optical measurements can also be done to assess material and device quality. The most basic measurement is assessing the wafers using optical microscopy. By looking at virgin epi-wafers under a high resolution optical microscope, some of the large defects at the wafer surface can be identified. For 4H-SiC material, defects such as micropipes and dislocations can be seen under the microscope. Using high resolution microscopes available at RMD and UVa, we will measure observable physical defects on the wafer samples for both 4H-SiC and silicon epi-wafer and give an estimation of densities of these defects. RMD and UVa will also attempt in using Emission Microscopy as another important failure analysis method to assess the quality of test wafers and devices. By reverse biasing the diode test structures at a very high electric field, the excess carriers accelerate and subsequently lose their energy and converted into photons. From the images of photo-emission captured by a CCD camera, we can look at the uniformity of the emission area. For high quality material and devices, the photoemission is very uniform, as depicted in Figure 10 a). When high concentrations of dislocations, micropipes, and process-induced defects are present, the photo-emission can be spotty, and lack uniformity, as shown in Figure 10 b).

D.8. Task 8: Write Phase-I Reports and Phase-II Proposal

For this task, RMD will summarize the efforts to develop our proposed device. In these reports, we will tabulate evaluated and simulated device response over expected range of use. The data enclosed in this report will provide the basis for our claim of device feasibility to be more completely developed in Phase II. At this stage, RMD expects to have carried out the research to establish the feasibility required to justify the more advanced development of the detector. The

Phase-II proposal will describe a plan for fabricating and testing of a GPD element prototype as well as small arrays of SSPMs, a development plan for implementing larger detector arrays for space-based gamma neutron spectrometers. The proposal will be prepared by the PI.

E. Phase I Performance Schedule

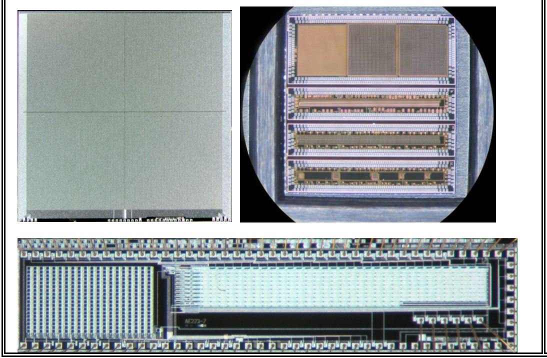
The following table indicates the schedule for the Phase I program over a nine month period. The key organizations are Radiation Monitoring Devices (RMD), Brown University (Brown), and the University of Virginia (UVa). The milestones are indicated in blue: generation of a design document, conceptual design review of the GPD, and technical design review of the wafer quality.

Tasks and Milestones	Organization	Month								
		1	2	3	4	5	6	7	8	9
1. Establish Design Specifications	RMD, Brown, UVa	■								
2. Identify Semiconductor	RMD, UVa	■	■	■						
3. Design GPD Elements	RMD, UVa	■	■	■	■					
Design Doc. for Virtual GPDs					🟦					
4. Simulation of GPD	RMD, UVa			■	■	■	■	■	■	■
Conceptual Design Review Doc.										🟦
5. Procure and Process Materials	RMD, UVa		■	■	■	■				
6. Baseline Studies at Temp.	Brown				■	■	■			
7. Meas. Baseline Wafer Char.	RMD						■	■	■	
Technical Review of Wafer Quality									🟦	
8. Reports and Proposal	RMD, Brown, UVa		■	■			■		■	■

F. Related Research or R&D

F.1. CMOS Silicon Solid-State Photomultipliers

RMD has been working with avalanche photodiodes since the 1970s and Geiger-mode diodes since the 1990s. RMD's Solid-state photomultiplier development started around 2002. Some of the most recent devices shown below are being developed with the aim of commercialization. The most recent SSPM designs developed by RMD use advanced CMOS processes (smaller feature sizes) to increase the number of structure options, complexity of on-chip circuitry, and better process control. These enhanced GPDs exhibit higher signal to noise ratios without additional dark counts when compared to existing SSPM pixels developed at RMD.



Top left: Large-area SSPM. The SSPM area is 1 cm x 1 cm with 2 x 2 arrays of 5 mm x 5 mm SSPMs. The device has 51,528, 30 μm x 30 μm pixels, giving the device a fill factor of 49%.

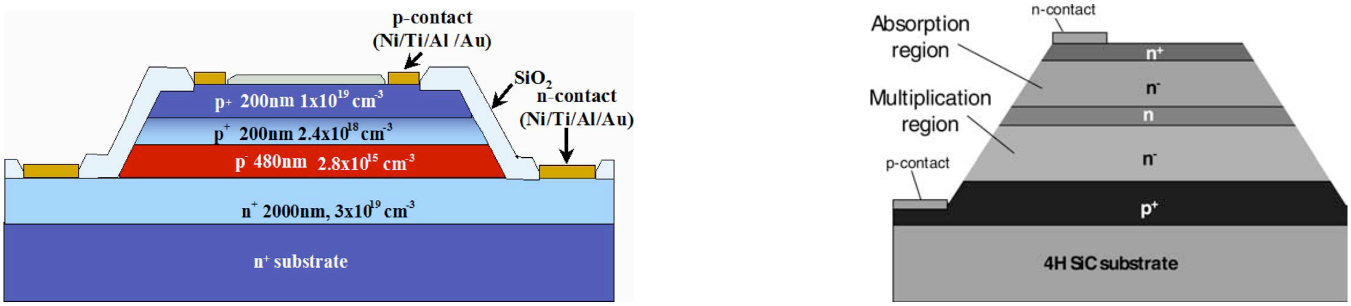
Top right: New generation of test SSPM and GPD elements fabricated in small feature size CMOS technology with improved detection efficiency and dark current.

Bottom: Digital event counting gamma-ray and neutron dosimeter and rate meter. Uses a CMOS SSPM with on-chip pulse-height sorting and RAM.

F.2. 4H-SiC APDs

From [17], 4H-SiC APDs with very low dark current have been developed. When biased for a photocurrent gain of 1000, a 100- μm-diameter device exhibits dark current of 5 pA (63 nA/cm^2), corresponding to primary multiplied dark current of 5 fA (63 pA/cm^2). The peak responsivity at unity gain is 93 mA/W (external quantum efficiency = 41%) at λ =280 nm. The excess noise factor corresponds to k = 0.1. Recent results from [16] show the development of using Geiger-mode avalanche photodiodes to construct an SSPM in 4H-SiC. The paper indicates that the material quality has to be addressed, as large numbers of defects in the device have been found, which might have a significant effect on the single photon diode yield compared to unity gain photodiodes. The devices fabricated show low dark count rates of several kHz for a 200-μm in diameter diode and a detection efficiency of 10% at 266 nm. A 12-pixel array was also fabricated.

These two devices provide the fundamental starting point for the development of a Geiger photodiode utilizing the designs developed at RMD. We focus on using a diode area much smaller than those reported, which will result in a few hot pixels. This results in a functional device, since the dark count rate will be dominated by the hot pixels. At any instant in time, the number of pixels triggered is most likely not to exceed the number of not pixels. Using larger pixels, the device becomes insensitive, as the large pixel will continuously trigger due to the thermally generated events from the defects in the device.



The left picture shows a schematic cross section of 4H-SiC APDs from [17], and the picture on the right shows a schematic of the 4H-SiC Geiger-mode APD from [16].

G. Principal Investigator and other Key Personal

The Principal Investigator on this project will be Dr. Erik B Johnson, Senior Scientist at Radiation Monitoring Devices, Inc, and he will lead the design and development of the proposed photodetector technology, and guide the activities of RMD's staff scientists and engineers in performing design, simulations, fabrication, and characterization of the prototype devices. James Christian is the group leader for the Instrument Research and Development Group at RMD, and with the other staff scientists at RMD, the group has worked on developing state-of-the-art photodetectors using silicon and AlGaAs. Jie Chen, a staff scientist at RMD, is an electric engineer with experience with semiconductor device design and fabrication. Prof. Joe Campbell has extensive experience with developing avalanche photodetectors using a variety of materials, from 4H-SiC to GaN. Prof. Gaitskell advises Jeremy Chapman (a graduate student at Brown University) and is the spokesman for the LUX experiment with extensive experience in the design and development of experiments used for dark matter searches. For a description of the key personnel and their qualifications, please refer to "Research and Related Senior/Key Person: Biographical Sketches". For a more detailed description of their roles in the program, please refer to the attached budget justification.

- Erik B. Johnson, Ph.D., Principal Investigator, RMD, Inc.
- James Christian, Ph.D., Group Leader, RMD, Inc.
- Xiao Jie Chen, Ph.D., Staff Scientist, RMD, Inc.
- Joe C. Campbell, Ph.D., Lucien Carr Professor, University of Virginia
- Richard Gaiskell, Ph.D., Professor, Brown University
- Jeremy Chapman, Graduate Student, Brown University

H. Facilities/Equipment

H.1. Radiation Monitoring Devices

RMD's laboratories occupy over 30,000 square feet and include equipment for many types of research and development work. RMD instrumentation work involves electronics development, software development, custom printed circuit board fabrication, CAD software, circuit development and equipment for high frequency oscillators, high-speed storage oscilloscopes, extensive sensor measuring equipment, and computerized signal generation analysis including MCG signal generation. Our mechanical engineering capabilities include AutoCAD, drafting, and an extensive machine shop with all the equipment required to design and fabricate a wide variety of mechanical prototype devices. A machine shop is available for any custom fabrication tasks and an electronics-engineering group is available for specialized design and construction of testing or readout circuitry.

The RMD electronics laboratory is multi-faceted with engineering specialties in analog and digital circuit design, software development, embedded system design and development and mechanical design. The laboratory includes a wealth of equipment includes digital oscilloscopes (to 11 GHz) computer, CAD software, software development platforms, x-y position systems, spectrum analyzer, lock in amplifier, and a wide range of analytical and modeling software.

RMD has fabrication resources including, diffusion furnaces, spin-coating stations, wet chemistry stations, wafer lapping and polishing set-ups, and microscope stations including electron microscopy. Additional device fabrication facilities include a high-vacuum evaporator with thickness monitoring capabilities, photomask aligner for applying photoresist on semiconductors, fume hoods, and clean areas for processing.

RMD has extensive facilities for the fabrication, testing, and packaging of sensors. Included are such items as crystal shaping equipment, cleaning and evacuation facilities, general bench and hood space for materials handling, glove boxes, and various facilities for crystal cutting, lapping, and polishing. RMD's laboratories meet all environmental laws and regulations. During the summer of 1999, the Massachusetts Water Resource Authority inspected our laboratories and revalidated our MWRA permit.

H.2. University of Virginia

University of Virginia Microelectronics Lab, Department of Electrical & Computer Engineering: The facilities include 3500 square feet of clean-room space equipped with all of the processing equipment necessary to fabricate state-of-the-art semiconductor devices, from epitaxial growth through die separation. Recently $2M in new equipment designated for photodiode processing has been added. These facilities are particularly beneficial for fast-turn-around process development as well as device-level materials and structure characterization. Fabrication facilities include the following: photolithography with back and front registration (Karl Suss with < 1 um resolution), SEM with focused ion beam, two e-beam evaporators, Oxford ICP-RIE, PECVD for SiO_2 and SiN, wet chemical etching bays, E-beam lithography if needed, rapid thermal anneal for contact formation, doped oxide furnaces, alpha step for feature height determination, ellipsometry, ion-implantation with external service

Additional facilities are available for the electrical, optical and RF characterization of solid-state materials, devices and circuits. The apparatus for complete characterization of linear-mode and Geiger-mode avalanche photodiodes is fully operational. Included are current-voltage, capacitance-voltage, quantum efficiency, excess noise factor, single photon detection efficiency, dark count rate, activation energy determination, and dark count rate versus frequency to measure afterpulsing effect. These measurements can be done from 4 K to 400K. Other characterization capabilities include bandwidth up to 100 GHz, spatial uniformity of photo-response, bit-error-rate measurements to 12.5

Gb/s, frequency dependence of impedance 1 MHz to 50 GHz, and transmission, reflection, and absorption of thin films, e.g., antireflection coatings. Campbell’s group has recently purchased an automated array tester to facilitate characterization of APD arrays.

H.3. Brown University

The Particle Astrophysics lab at Brown University is run by Professor Gaitskell. The lab facilities include two vacuum chambers and the ability to cool them to 77K and 175K (using ethanol mixed with LN). The lab has ~10kg of research grade xenon for use in these cryogenic systems. There is a circulation system with a SAES monoTorr getter for removing impurities from the xenon, and an assortment of radioactive sources for calibration. The lab has fully functional data acquisition, high voltage, and detector monitoring systems to support the research. In addition a new lab space has been renovated with a 6ft x 8ft water tank to act as a shield for low background operation of liquid xenon detectors.

I. Consultants and Subcontractors

I.1. Consultant: Joe C. Campbell

School of Engineering and Applied Science
Dept. of Elec. and Computer Engineering
351 McCormick Road
P.O. Box 400743
Charlottesville, VA 22904

434-243-2068
jcc7s@virginia.edu
Consulting Fee: $4,500.00

Prof. Campbell will consult RMD on the design of the Geiger photodiodes to be developed within this program, and his involvement has been outline within the work plan.

I.2. Subcontract: University of Virginia

Dept of Elec. and Computer Engineering
University of Virginia
Main Office: Room C210 Thornton Hall
351 McCormick Road, PO Box 400743
Charlottesville, VA 22904-4743

Phone: 434-924-3960
Fax: 434-924-8818
Email: eceinfo@virginia.edu
Subcontract Cost: $20,350.07

The University of Virginia will employ students for conducting simulations and processing of wafers.

I.3. Subcontract: Brown University

Prof. Richard Gaitskell
Dept. of Physics
Brown University
Box 1843
Providence, RI 02912

Phone: (401) 863 9783
Fax: (401) 863 2024
E-mail: gaitskell@brown.edu
Subcontract Cost: $17,850.00

Prof. Gaitskell will advise the work by Jeremy Chapman for the measurements on temperature.

J. Bibliography & References Cites

[1] D. S. Akerib, et al., "Data acquisition and readout system for the LUX dark matter experiment," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 668, pp. 1-8, 2012.
[2] R. J. McIntyre, "Recent developments in silicon avalanche photodiodes," *Measurement*, vol. 3, pp. 146-52, 1985.
[3] S. Vasile, et al., "Fast avalanche photodiode detectors for the Superconducting Super Collider," presented at Semicond. for RT Rad. Detector Applications, 1993.
[4] H. Dautet, et al., "Photon counting techniques with silicon avalanche photodiodes," *Appl. Opt. (USA)*, vol. 32, pp. 3894-900, 1993.

[5] S. Cova, et al., "Avalanche photodiodes for near-infrared photon-counting," 1995.
[6] P. Buzhan, et al., "The Advanced Study of Silicon Photomultiplier," presented at Advanced Technology and Particle Physics (ICATPP-7), 2001.
[7] A. G. Rochas, M.; Furrer, B.; Besse, P. A.; Popovic, R. S.; Ribordy, G.; Gisin, N., "Single photon detector fabricated in a complementary metal–oxide–semiconductor high-voltage technology," *Review of Scientific Instruments*, vol. 74, pp. 6263-6270, 2003.
[8] J. F. Christian, et al., "Advances in CMOS solid-state photomultipliers for scintillation detector applications," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 624, pp. 449-458, 2010.
[9] C. J. Stapels, et al., "Direct photon-counting scintillation detector readout using an SSPM," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 579, pp. 87-90, 2007.
[10] E. B. Johnson, et al., "Energy Resolution in CMOS SSPM Detectors Coupled to an LYSO Scintillator," *IEEE Transactions on Nuclear Science*, vol. 56, pp. 1024-1032, 2009.
[11] L. R. Canfield, et al., "Absolute silicon photodiodes for 160 nm to 254 nm photons," *Metrologia*, vol. 35, pp. 329, 1998.
[12] R. Chandrasekharan, et al., "High efficiency detection of argon scintillation light of 128 nm using LAAPDs," presented at Nuclear Science Symposium Conference Record, 2005.
[13] K. Kamada, et al., "Pr:$Lu_3Al_5O_{12}$ (LuAG) scintillator read-out using UV-enhanced avalanche photodiode," presented at Nuclear Science Symposium Conference Record, 2009.
[14] C. M. Pepin, et al., "New UV-enhanced, ultra-low noise silicon avalanche photodiode for radiation detection and medical imaging," presented at Nuclear Science Symposium Conference Record (NSS/MIC), 2010.
[15] X. Bai, et al., "Ultraviolet Single Photon Detection With Geiger-Mode 4H-SiC Avalanche Photodiodes," *Photonics Technology Letters, IEEE*, vol. 19, pp. 1822-1824, 2007.
[16] A. Vert, et al., "SiC avalanche photodiodes and photomultipliers for ultraviolet and solar-blind light detection," *physica status solidi (a)*, vol. 206, pp. 2468-2477, 2009.
[17] X. Bai, et al., "High Detection Sensitivity of Ultraviolet 4H-SiC Avalanche Photodiodes," *Quantum Electronics, IEEE Journal of*, vol. 43, pp. 1159 - 1162, 2007.
[18] L. Shi, et al., "Surface-Charge-Collection-Enhanced High-Sensitivity High-Stability Silicon Photodiodes for DUV and VUV Spectral Ranges," *Electron Devices, IEEE Transactions on*, vol. PP, pp. 1-7, 2012.
[19] Personal Communication with J. C. Campbell
[20] F. Nava, et al., "Silicon carbide and its use as a radiation detector material," *Measurement Science and Technology*, vol. 19, pp. 102001, 2008.
[21] M. Shur, *SiC Materials and Devices*: World Scientific Publishing, 2006.
[22] H. Zhu, et al., "4H–SiC ultraviolet avalanche photodetectors with low breakdown voltage and high gain," *Solid-State Electronics*, vol. 53, pp. 7-10, 2009.
[23] F. Yan, et al., "4H-SiC visible blind UV avalanche photodiode," *Electronics Letters*, vol. 35, pp. 929-930, 1999.
[24] J. C. Campbell, "Recent Advances in Telecommunications Avalanche Photodiodes," *Journal of Lightwave Technology*, vol. 25, pp. 109-121, 2007.
[25] L. C. Yu, et al., "Modeling and design of a monolithically integrated power converter in SiC," *Solid-State Electronics*, vol. 52, pp. 1625-1630, 2008.
[26] K. Ohtsuka, et al., "Leakage current in Ti/4H-SiC Schottky barrier diode," *Physica B: Condensed Matter*, vol. 376-377, pp. 370-373, 2006.
[27] P. Barton, "Silicon Photomultipliers for Scintillation Detection Systems," in *Nuclear Engineering and Radiological Sciences*. Ann Arbor: University of Michigan, 2011.

Low-Noise Solid-State Photomultiplier for Dark Matter Searches

Principal Investigator: Dr. Erik B. Johnson, Senior Scientist **Topic:** 42. A.

Bibliography & References

[1] D. S. Akerib, et al., "Data acquisition and readout system for the LUX dark matter experiment," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 668, pp. 1-8, 2012.

[2] R. J. McIntyre, "Recent developments in silicon avalanche photodiodes," *Measurement*, vol. 3, pp. 146-52, 1985.

[3] S. Vasile, et al., "Fast avalanche photodiode detectors for the Superconducting Super Collider," presented at Semicond. for RT Rad. Detector Applications, 1993.

[4] H. Dautet, et al., "Photon counting techniques with silicon avalanche photodiodes," *Appl. Opt. (USA)*, vol. 32, pp. 3894-900, 1993.

[5] S. Cova, et al., "Avalanche photodiodes for near-infrared photon-counting," 1995.

[6] P. Buzhan, et al., "The Advanced Study of Silicon Photomultiplier," presented at Advanced Technology and Particle Physics (ICATPP-7), 2001.

[7] A. G. Rochas, M.; Furrer, B.; Besse, P. A.; Popovic, R. S.; Ribordy, G.; Gisin, N., "Single photon detector fabricated in a complementary metal–oxide–semiconductor high-voltage technology," *Review of Scientific Instruments*, vol. 74, pp. 6263-6270, 2003.

[8] J. F. Christian, et al., "Advances in CMOS solid-state photomultipliers for scintillation detector applications," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 624, pp. 449-458, 2010.

[9] C. J. Stapels, et al., "Direct photon-counting scintillation detector readout using an SSPM," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 579, pp. 87-90, 2007.

[10] E. B. Johnson, et al., "Energy Resolution in CMOS SSPM Detectors Coupled to an LYSO Scintillator," *IEEE Transactions on Nuclear Science*, vol. 56, pp. 1024-1032, 2009.

[11] L. R. Canfield, et al., "Absolute silicon photodiodes for 160 nm to 254 nm photons," *Metrologia*, vol. 35, pp. 329, 1998.

[12] R. Chandrasekharan, et al., "High efficiency detection of argon scintillation light of 128 nm using LAAPDs," presented at Nuclear Science Symposium Conference Record, 2005.

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[15] X. Bai, et al., "Ultraviolet Single Photon Detection With Geiger-Mode 4H-SiC Avalanche Photodiodes," *Photonics Technology Letters, IEEE*, vol. 19, pp. 1822-1824, 2007.

[16] A. Vert, et al., "SiC avalanche photodiodes and photomultipliers for ultraviolet and solar-blind light detection," *physica status solidi (a)*, vol. 206, pp. 2468-2477, 2009.

[17] X. Bai, et al., "High Detection Sensitivity of Ultraviolet 4H-SiC Avalanche Photodiodes," *Quantum Electronics, IEEE Journal of*, vol. 43, pp. 1159 - 1162, 2007.

[18] L. Shi, et al., "Surface-Charge-Collection-Enhanced High-Sensitivity High-Stability Silicon Photodiodes for DUV and VUV Spectral Ranges," *Electron Devices, IEEE Transactions on*, vol. PP, pp. 1-7, 2012.

[19] Personal Communication with J. C. Campbell

[20] F. Nava, et al., "Silicon carbide and its use as a radiation detector material," *Measurement Science and Technology*, vol. 19, pp. 102001, 2008.

[21] M. Shur, *SiC Materials and Devices*: World Scientific Publishing, 2006.

[22] H. Zhu, et al., "4H–SiC ultraviolet avalanche photodetectors with low breakdown voltage and high gain," *Solid-State Electronics*, vol. 53, pp. 7-10, 2009.

[23] F. Yan, et al., "4H-SiC visible blind UV avalanche photodiode," *Electronics Letters*, vol. 35, pp. 929-930, 1999.

[24] J. C. Campbell, "Recent Advances in Telecommunications Avalanche Photodiodes," *Journal of Lightwave Technology*, vol. 25, pp. 109-121, 2007.

[25] L. C. Yu, et al., "Modeling and design of a monolithically integrated power converter in SiC," *Solid-State Electronics*, vol. 52, pp. 1625-1630, 2008.

[26] K. Ohtsuka, et al., "Leakage current in Ti/4H-SiC Schottky barrier diode," *Physica B: Condensed Matter*, vol. 376-377, pp. 370-373, 2006.

[27] P. Barton, "Silicon Photomultipliers for Scintillation Detection Systems," in *Nuclear Engineering and Radiological Sciences*. Ann Arbor: University of Michigan, 2011.

Low-Noise Solid-State Photomultiplier for Dark Matter Searches

Principal Investigator: Dr. Erik B. Johnson, Senior Scientist **Topic:** 42. A.

Facilities

Radiation Monitoring Devices

RMD's laboratories occupy over 30,000 square feet and include equipment for many types of research and development work. RMD instrumentation work involves electronics development, magnetic sensor development, software development, custom printed circuit board fabrication, CAD software, circuit development and debug equipment for high frequency oscillators, high-speed storage oscilloscopes, extensive sensor measuring equipment, and computerized signal generation analysis including MCG signal generation. Our mechanical engineering capabilities include AutoCAD, drafting, and an extensive machine shop with all the equipment required to design and fabricate a wide variety of mechanical prototype devices. RMD has fabrication resources including, diffusion furnaces, spin-coating stations, wet chemistry stations, wafer lapping and polishing set-ups, and microscope stations including electron microscopy.

RMD has extensive facilities for the fabrication, testing, and packaging of sensors. Included are such items as crystal shaping equipment, cleaning and evacuation facilities, general bench and hood space for materials handling, glove boxes, and various facilities for crystal cutting, lapping, and polishing. RMD's laboratories meet all environmental laws and regulations. During the summer of 1999, the Massachusetts Water Resource Authority inspected our laboratories and revalidated our MWRA permit.

A machine shop is available for any custom fabrication tasks and an electronics-engineering group is available for specialized design and construction of testing or readout circuitry.

University of Virginia

University of Virginia Microelectronics Lab, Department of Electrical & Computer Engineering: The facilities include 3500 square feet of clean-room space equipped with all of the processing equipment necessary to fabricate state-of-the-art semiconductor devices, from epitaxial growth through die separation. Recently $2M in new equipment designated for photodiode processing has been added. These facilities are particularly beneficial for fast-turn-around process development as well as device-level materials and structure characterization.

Additional facilities are available for the electrical, optical and RF characterization of solid-state materials, devices and circuits. The apparatus for complete characterization of linear-mode and Geiger-mode avalanche photodiodes is fully operational. Included are current-voltage, capacitance-voltage, quantum efficiency, excess noise factor, single photon detection efficiency, dark count rate, activation energy determination, and dark count rate versus frequency to measure afterpulsing effect. These measurements can be done from 4 K to 400K. Other characterization capabilities include bandwidth up to 100 GHz, spatial uniformity of photo-response, bit-error-rate measurements to 12.5 Gb/s, frequency dependence of impedance 1 MHz to 50 GHz, and transmission, reflection, and absorption of thin films, e.g., antireflection coatings. Campbell’s group has recently purchased an automated array tester to facilitate characterization of APD arrays.

Low-Noise Solid-State Photomultiplier for Dark Matter Searches

Principal Investigator: Dr. Erik B. Johnson, Senior Scientist **Topic:** 42. A.

Equipment

Radiation Monitoring Devices

RMD instrumentation work involves electronics development, magnetic sensor development, software development, custom printed circuit board fabrication, CAD software, circuit development and debug equipment for high frequency oscillators, high-speed storage oscilloscopes, extensive sensor measuring equipment, and computerized signal generation analysis including MCG signal generation. Our mechanical engineering capabilities include AutoCAD, drafting, and an extensive machine shop with all the equipment required to design and fabricate a wide variety of mechanical prototype devices.

RMD has fabrication resources including, diffusion furnaces, spin-coating stations, wet chemistry stations, wafer lapping and polishing set-ups, and microscope stations including electron microscopy. Additional device fabrication facilities include a high-vacuum evaporator with thickness monitoring capabilities, photomask aligner for applying photoresist on semiconductors, fume hoods , and clean areas for processing.

The RMD electronics laboratory is multi-faceted with engineering specialties in analog and digital circuit design, software development, embedded system design and development and mechanical design. The laboratory includes a wealth of equipment includes digital oscilloscopes (to 11 GHz) computer, CAD software, software development platforms, x-y position systems, spectrum analyzer, lock in amplifier, and a wide range of analytical and modeling software.

RMD maintains a local area network that connects all scientific staff PCs. Some laboratory PCs are also networked, while others perform independently, typically assigned to a singular data acquisition task. All are MS Windows or DOS based. RMD provides all scientific staff with individual desks and office areas. Also available is a library of approximately 300 volumes covering subjects of material science, radiation physics, electronics and related topics.

University of Virginia

The University of Virginia's fabriation facilities include the following:

- Photolithography with back and front registration (Karl Suss with < 1 um resolution)
- SEM with focused ion beam
- Two e-beam evaporators
- Oxford ICP-RIE
- PECVD for SiO_2 and SiN
- Wet chemical etching bays
- E-beam lithography if needed
- Rapid thermal anneal for contact formation
- Doped oxide furnaces
- Alpha step for feature height determination
- Ellipsometry

- Ion-implanation with external service

Brown University

The Particle Astrophysics lab at Brown University is run by Professor Gaitskell. The lab facilities include two vacuum chambers and the ability to cool them to 77K and 175K (using ethanol mixed with LN). The lab has ~10kg of research grade xenon for use in these cryogenic systems. There is a circulation system with a SAES monoTorr getter for removing impurities from the xenon, and an assortment of radioactive sources for calibration. The lab has fully functional data acquisition, high voltage, and detector monitoring systems to support the research. In addition a new lab space has been renovated with a 6ft x 8ft water tank to act as a shield for low background operation of liquid xenon detectors.

OMB Number: 4040-0001
Expiration Date: 06/30/2011

RESEARCH & RELATED Senior/Key Person Profile (Expanded)

PROFILE - Project Director/Principal Investigator

Prefix:
* First Name: Erik
Middle Name:
* Last Name: Johnson
Suffix:
Position/Title: Scientist
Department: Research
Organization Name: Radiation Monitoring Devices, Inc.
Division: Instrument Research and Dev.
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County/ Parish:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* Zip / Postal Code: 02472-4699
* Phone Number: 617-668-6801
Fax Number:
* E-Mail: EJohnson@rmdinc.com

Credential, e.g., agency login:

*** Project Role:** PD/PI
Other Project Role Category:

Degree Type: Ph.D
Degree Year: 2003

***Attach Biographical Sketch** 1234-P13-026_Biosketch_EJ.pdf Add Attachment Delete Attachment View Attachment
Attach Current & Pending Support 1235-P13-026_Support Report_E Add Attachment Delete Attachment View Attachment

PROFILE - Senior/Key Person 1

Prefix:
* First Name: James
Middle Name:
* Last Name: Christian
Suffix:
Position/Title: Scientist
Department: Research
Organization Name: Radiation Monitoring Devices, Inc.
Division: Instrument Research & Dev.
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County/ Parish:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* Zip / Postal Code: 02472-4699
* Phone Number: 617-668-6801
Fax Number:
* E-Mail: JChristian@rmdinc.com

Credential, e.g., agency login:

*** Project Role:** Other (Specify)
Other Project Role Category: Scientist

Degree Type: Ph.D
Degree Year: 1992

***Attach Biographical Sketch** 1236-P13-026_Biosketch_JC.pdf Add Attachment Delete Attachment View Attachment
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RESEARCH & RELATED Senior/Key Person Profile (Expanded)

PROFILE - Senior/Key Person 2

Prefix:
* First Name: Xiao Jie
Middle Name:
* Last Name: Chen
Suffix:
Position/Title: Scientist
Department: Research
Organization Name: Radiation Monitoring Devices, Inc.
Division: Instrument Research & Dev.
* Street1: 44 Hunt St.
Street2:
* City: Watertown
County/ Parish:
* State: MA: Massachusetts
Province:
* Country: USA: UNITED STATES
* Zip / Postal Code: 02472-4699
* Phone Number: 617-668-6801
Fax Number:
* E-Mail: JChen@rmdinc.com

Credential, e.g., agency login:

*** Project Role:** Other (Specify)
Other Project Role Category: Scientist

Degree Type: Ph.D
Degree Year: 2008

***Attach Biographical Sketch** 1238-P13-026_Biosketch_XC.pdf Add Attachment Delete Attachment View Attachment
Attach Current & Pending Support 1239-P13-026_Support Report_X Add Attachment Delete Attachment View Attachment

PROFILE - Senior/Key Person 3

Prefix:
* First Name: Richard
Middle Name:
* Last Name: Gaitskill
Suffix:
Position/Title: Associate Professor
Department: Physics
Organization Name: Brown University
Division:
* Street1: Box 1843
Street2:
* City: Providence
County/ Parish:
* State: RI: Rhode Island
Province:
* Country: USA: UNITED STATES
* Zip / Postal Code: 02912-0001
* Phone Number: 401-863-9783
Fax Number: 401-863-2024
* E-Mail: gaitskell@brown.edu

Credential, e.g., agency login:

*** Project Role:** Other (Specify)
Other Project Role Category: Subcontract

Degree Type:
Degree Year:

***Attach Biographical Sketch** 1240-P13-026_RGaitskell Brown Add Attachment Delete Attachment View Attachment
Attach Current & Pending Support Add Attachment Delete Attachment View Attachment

RESEARCH & RELATED Senior/Key Person Profile (Expanded)

PROFILE - Senior/Key Person 4

Prefix:

* First Name: Joe

Middle Name:

* Last Name: Campbell

Suffix:

Position/Title: Professor

Department: Engineering

Organization Name: University of Virginia

Division:

* Street1: 351 McCormick Rd

Street2: PO Box 400743

* City: Charlottesville

County/ Parish:

* State: VA: Virginia

Province:

* Country: USA: UNITED STATES

* Zip / Postal Code: 22904-4743

* Phone Number: 434-924-2068

Fax Number: 434-924-8818

* E-Mail: jcc7s@virginia.edu

Credential, e.g., agency login:

*** Project Role:** Other (Specify)

Other Project Role Category: Consultant

Degree Type:

Degree Year:

***Attach Biographical Sketch** 1241-P13-026_JCampbell Bio.do Add Attachment Delete Attachment View Attachment

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BIOGRAPHICAL SKETCH - James Christian, Ph.D. – Director of Instrument R&D

Education and Training:

Loyola College, Baltimore, MD	B.S.	1984	Biology & Chemistry
S.U.N.Y. at Stonybrook, Stonybrook, NY	Ph.D.	1992	Physical Chemistry
A.M.O.L.F., Amsterdam, The Netherlands	Post-Doc	1994	Physics
Northeastern University, Boston, MA	Post-Doc	1998	Biophysics

Research and Professional Experience:

Dr. James F. Christian received his Ph.D. in the field of Physical Chemistry from the State University of New York (S.U.N.Y.) at Stony Brook in August 1992, studying Ion-C60 Collisions with a tandem mass spectrometer system. From 1992 to 1994, Dr. Christian worked at the Institute for Atomic and Molecular Physics located in Amsterdam, Holland as a postdoctoral fellow, where he studied the dynamics of electrons in large orbits about atomic Rubidium using a novel, time-resolved spectroscopy that measured the interference between a pump and probe Rydberg wavepacket. As a Postdoctoral Fellow at Northeastern University from 1994 to 1998, Dr. Christian studied heme proteins using both frequency and time-resolved optical spectroscopy.

In September 1998, Dr. Christian joined Radiation Monitoring Devices, Inc. He participated as the key investigator in the development of a photon-counting detection platform for micro-scale analysis systems using Geiger-mode micro-avalanche photodiode arrays. During the course of this work, he developed high-bandwidth, active-quenching electronics that increased the maximum photon counting rate, which substantially extended the dynamic range of the micro-avalanche photodiode detectors. As the Director of the Instrument Research and Development Group at RMD since 2002, Dr. Christian has been leading the development and characterization of CMOS solid-state photomultiplier (SSPM) detectors, which are arrays of Geiger-mode micro-avalanche photodiodes, and the development of coded-aperture gamma-ray imaging systems. The group has pioneered the development of large area, 1 cm x 1 cm, SSPMs, position-sensitive SSPMs, the description of the binomial noise characteristics of these devices, and their relation to energy resolution in scintillation-based gamma-ray spectroscopy applications. The group has also contributed to the design of a Stand-off Radiation Detection System (SORDS) that uses both coded-aperture and Compton imaging techniques.

Selected Publications:

1. A.T.N. Kumar, L. Zhu, J.F. Christian, A.A. Demidov, and P.M. Champion, "On the Rate Distribution Analysis of Kinetic Data Using the Maximum Entropy Method: Applications to Myoglobin Relaxation on the Nanosecond and Femtosecond Timescales", J. Phys. Chem. B **105**, 7847 (2001).
2. M.L. Chabinyc, D.T. Chiu, J.C. McDonald, A.D. Stroock, J.F. Christian, A.M. Karger, and G.M. Whitesides,"An Integrated Fluorescence Detection System in Poly(dimethylsiloxane) for Microfluidic Applications", Anal. Chem. **73**, 4491 (2001).
3. M. Woodring, D. Beddingfield, D. Souza, G. Entine, M. Squillante, James Christian, A. Kogan, “Advanced multi-dimensional imaging of gamma-ray radiation”, Nuclear Instruments and Methods in Physics Research **505**, 415 (2003).
4. J.F. Christian, M.R. Squillante, M. Woodring. G. Entine, “Portable Video/Gamma Camera for Surveillance, Safeguards, Treaty Verification and Area Monitoring”, Proc. 45th INMM Annual Meeting, Orlando, FL, July 18-22, (2004).
5. C. Stapels, W. G. Lawrence, M. R. Squillante, G. Entine, F. L. Augustine, and J. Christian, "CMOS-based, Position-Sensitive Solid-state Photomultiplier," presented at IEEE NSS/MIC, Oct. 26-29, San Juan, Puerto Rico (2005).

6. C.J. Stapels, W.G. Lawrence, F.L. Augustine, and J.F. Christian, “Characterization of a CMOS Geiger Photodiode Pixel”, IEEE Transactions on Electron Devices **53**, 631 (2006).
7. C. J. Stapels, W. G. Lawrence, F. L. Augustine, and J. F. Christian, "CMOS Solid-State Photomultiplier for Detecting Scintillation Light in Harsh Environments," presented at SNIC Symposium www-conf.slac.stanford.edu/snic/proceedings/status.htm, SLAC Stanford, CA, April 3-6, (2006).
8. C. J. Stapels, M. R. Squillante, W. G. Lawrence, F. L. Augustine, and J. F. Christian, "CMOS-based avalanche photodiodes for direct particle detection," Nucl Instrum Methods Phys Res Sect A, **579**(1): p. 94-98 (2007).
9. C. J. Stapels, M. R. Squillante, W. G. Lawrence, F. L. Augustine, and J. F. Christian, "Direct photon-counting scintillation detector readout using an SSPM," Nuclear Instruments and Methods in Physics Research Section A, vol. **579**, pp. 87-90 (2007).
10. C. J. Stapels, E. B. Johnson, R. Sia, F. L. Augustine, and J. F. Christian, "Integrated signal processing of CMOS Geiger photodiode arrays," 2007 IEEE Nuclear science symposium and medical imaging conference, vol. **6**, pp. 4586 - 4590 (2007).
11. J. F. Christian, R. Sia, P. Dokhale, I. Shestakova, V. Nagarkar, K. Shah, C. J. Stapels, J. M. Ryan, J. Macri, U. Bravar, K.-N. Leung, M. R. Squillante, and E. B. Johnson, "Nuclear material detection techniques," Optics and Photonics in Global Homeland Security IV, vol. **6945** (2008).
12. C. J. Stapels, W. G. Lawrence, R. S. Gurjar, E. B. Johnson, and J. F. Christian, "CMOS Geiger photodiode array with integrated signal processing for imaging of 2D objects using quantum dots," Infrared Systems and Photoelectronic Technology III, vol. **7055**, pp. 70550S-9 (2008).
13. E.B. Johnson, P. Barton, K. Shah, C.J. Stapels, D.K. Wehe, J.F. Christian. Energy Resolution in CMOS SSPM Detectors Coupled to an LYSO Scintillator. IEEE Transactions on Nuclear Science, **56** (3), 1024-1032 (2009).
14. Christian JF, Stapels CJ, Johnson EB, McClish M, Dokhale P, Shah KS, Mukhopadhyay S, Chapman E, and Augustine FL. Advances in CMOS solid-state photomultipliers for scintillation detector applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. **624** (2), 449-458 (2010).
15. E.B. Johnson, C.J. Stapels, X.J. Chen, F.L. Augustine, J.F. Christian, Large-Area CMOS Solid-State Photomultipliers and Recent Developments. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. **652**, 494-499 (2011).
16. J.F. Christian, K.S. Shah, and M.R. Squillante “Advances in CMOS SSPM Detectors” in Biological and Medical Sensor Technologies, K. Iniewski ed., CRC Press (Boca Raton, FL), 301-338 (2012).

Synergistic Activities:

1. Member of IEEE
2. Member of the American Physical Society, the American Chemical Society and SPIE
3. He has reviewed papers for TED (Transactions on Electron Devices), and NIMA (Nuclear Instrumentation and Methods A).
4. He has served on NIH review panels.

BIOGRAPHICAL SKETCH – Xiaojie Chen, Ph.D.
Staff Scientist, Instrument Research and Development Group

Education and Training:

New Mexico State University	B.S.	2002	Electrical and Computer Engineering
University of Arizona	M.S.	2005	Electrical and Computer Engineering
Arizona State University	Ph.D.	2008	Electrical and Computer Engineering

Research and Professional Experience:

Dr. Chen completed his B.S. in Electrical and Computer Engineering at New Mexico State University (NMSU) as a Crimson Scholar. In 2003, as a second year graduate student he joined a research group at the University of Arizona studying the effects of high energy radiation on semiconductor devices, and he completed his M.S. degree in 2005. Based on his master's work, he went on to obtain his Ph.D degree at Arizona State University on the characterization and modeling of the effect of radiation on silicon devices and circuits.

Dr. Chen focused on the characterization and modeling of radiation effects on semiconductor devices during his years as a graduate student. In particular, he worked on radiation damage characterization, modeling and prevention on silicon based bipolar devices and circuits used in harsh environment electronic systems, ranging from satellites to space exploration vehicles. His research efforts as a Ph.D student in the area of radiation effects have earned him an Institute of Electrical and Electronic Engineers (IEEE)/Nuclear and Plasma Science Society (NPSS) Phelps Award and a Best Paper Award at IEEE Nuclear and Space Radiation Effects Conference in 2007. After the completion of his doctorate, Dr. Chen continued his study on radiation damage effects on semiconductor devices at Arizona State University as a post-doctoral fellow. During this period, he continued the modeling efforts on radiation dose rate sensitivity in silicon devices as well as radiation damage mechanisms in GaAs photovoltaic devices.

In June of 2009, Dr. Chen joined Radiation Monitoring Devices, Inc. His current interests are focused on the development of novel devices and systems for radiation and nuclear material detection, monitoring, and tracking. Presently, he is involved in projects related to the development and applications of solid state photo-detectors such as CMOS solid-state-photomultipliers (SSPM), silicon avalanche photodiodes, and photo-detectors based on wide-band-gap semiconductor materials. Such photo-detector applications include scintillation-based radiation sensors and detectors for nuclear and high energy physics, space exploration and satellite systems, as well as portable monitors and dosimeters for homeland security..

Dr. Chen is a member of IEEE, NPSS and SPIE. He has published and presented more than 30 Journal and conference papers in the area of nuclear and radiation detection, solid state physics and photonics, and radiation effects on solid-state devices. The following is a partial list of conference papers and publications.

Selected Conference Papers and Publications

1. **Xiao Jie Chen**, Erik B. Johnson, Christopher J. Stapels, Chad Whitney, and James F. Christian, "Next Generation CMOS SSPMs for scintillation detection applications", IEEE Symposium on Radiation Measurements and Applications, 2012
2. Mark D. Hammig, **Xiao Jie Chen**, Joseph C. Campbell, Wenlu Sun, Taehoon Kang, Erik B. Johnson and James F. Christian, "Development of $Al_{0.8}Ga_{0.2}As$ Photodiodes for use in Wide Band-Gap Solid-State Photomultipliers", IEEE Symposium on Radiation Measurements and Applications, 2012.
3. **Xiao Jie Chen**, Erik B. Johnson, Christopher J. Stapels, Chad Whitney, and James F. Christian, "High Performance Geiger Photodiodes in a 0.18um Feature size

CMOS Technology", IEEE Nuclear Science Symposium, 2011.

4. **Xiao Jie Chen**, Erik B. Johnson, Christopher J. Stapels, Eric Chapman, Guy Alberghini, Sharmistha Mukhopadhyay, and James F. Christian, “A Space Dosimeter Based on CMOS Solid State Photomultipliers”, IEEE Trans. On Nuclear Science, Vol 57, No 6, 2010.
5. **X. J. Chen**, Erik B. Johnson, Christopher J. Stapels, Eric Chapman, Sharmistha Mukhopadhyay, James F. Christian, “Optical and Noise Performance of CMOS Solid-State Photomulitpliers”, SPIE Optics & Photonics Conference, 2010.
6. Erik B. Johnson, **Xiao Jie Chen**, Rory Miskimen, Drew Von Maluski, Christopher J. Stapels, Sharmistha Mukhopadhyay, Frank Augustine, James F. Christian, “Characteristics of CMOS Avalanche Photodiodes at Cryogenic Temperatures”,IEEE NSS, Orlando, USA, 2009.
7. E. B. Johnson*, C. J. Stapels, P. Dokhale, M. McClish, **X. J. Chen**, S. Mukhopadhyay, E. Chapman, K. Shah, and J. F. Christian, “Recent Developments for CMOS Solid-State Photomultipliers with Integrated Signal Processing”, IEEE NSS, Orlando, USA, 2009.
8. Erik B. Johnson, Eric Chapman, **Xiao Jie Chen**, Sharmistha Mukhopadhyay, Christopher J. Stapels, and James F. Christian, “Performance Characteristics of the CMOS SSPM Tissue-Equivalent Space Dosimeter”, IEEE Aerospace Conference, 2009.
9. **X. J. Chen**, H. J. Barnaby, P. Adell, R. L. Pease, B. Vermeire, and K. E. Holbert, "Modeling the Dose Rate Response and the Effects of Hydrogen in Bipolar Technologies," Nuclear Science, IEEE Transactions on, vol. 56, pp. 3196-3202, 2009.
10. **X. J. Chen**, H. J. Barnaby, J. H. Warner, S. R. Messenger, R. J. Walters, “Non-linear Behaviors of Dark Current Slope in p+n GaAs Solar Cells Following Proton Irradiations, Photovoltaic Specialists Conference, 2009.
11. R. L. Pease, P. Adell, B. G. Rax, **X. J. Chen**, H. J. Barnaby, K. E. Holbert, H. P. Hjalmarson, "The Effects of Hydrogen on the Enhanced Low Dose Rate Sensitivity (ELDRS) of Bipolar Linear Circuits," IEEE Trans. Nucl. Sci., vol. 55, pp. 3169-3173, 2008.
12. **X. J. Chen**, H. J. Barnaby, "The effects of radiation-induced interface traps on base current in gate bipolar test structures", Solid State Electronics, Vol. 52, No. 5, 2008.
13. J. E. Seiler, S. McClure, and P. C. Adell, "Mechanisms of Enhanced Radiation-Induced Degradation due to Excess Molecular Hydrogen in Bipolar Oxides," IEEE Trans. Nucl. Sci., vol. 54, 2007.
14. **X. J. Chen**, H. J. Barnaby, R. D. Schrimpf, D. M. Fleetwood, R. L. Pease, R. D. Platteter. “Nature of interface defect buildup in gated bipolar devices under low dose rate irradiation,” IEEE Trans. on Nuclear Science, vol. 53, pp. 3649-3654, 2006.
15. H. J. Barnaby, M. L. Mclain, I. S. Esqueda, **X. J. Chen**., "Modeling Ionizing Radiation Effects in Solid State Materials and CMOS Devices," Custom Integrated Circuits Conference, 2008.

Richard Gaitskell
Associate Professor, Brown University

EDUCATION

1989–93	St John’s College, Oxford University, D. Phil. in Physics, (Dark Matter Detector Development)
1988–89	London Business School, Corporate Finance Evening Course
1982–85	St John's College, Oxford University, BA Hons Degree in Physics

PROFESSIONAL EXPERIENCE

Prof. Rick Gaitskell (Brown University) is the co-spokesperson of the LUX (Large Underground Xenon) dark matter experiment. He was a founding PI (principle investigator) of the experiment in 2007. LUX is the latest venture in his 23 year career, working at underground laboratories, looking for particle dark matter. Rick Gaitskell started this work at Oxford University in the UK, and then continued it at Berkeley, Stanford, University College London, and now at Brown University.

LUX represents a major step forward in our quest to directly detect the dark matter particles which are likely the dominant form of matter in our Universe. After two years of construction and testing of LUX at the surface facility at Sanford Lab (South Dakota), we have moved the detector into the new deep underground laboratory area and will turning it on at the end of 2012. Results should come very quickly. After only 14 days of running LUX underground, we expect it to surpass the sensitivity of all previous dark matter direct search experiments. If particle dark matter is present in our galaxy LUX will have a significant opportunity to detect it.

Gaitskell is also a founding member, and was the first spokesperson of the LZ experiment. LZ is a new dark matter experiment, 20 times larger than LUX, to be operated in the Sanford Lab from 2016 onwards.

RECENT PUBLICATIONS

1. R.J.Gaitskell, "Direct Detection of Dark Matter", Annu. Rev. Nucl. and Part. Sci. 54 (2004) 315-359.
2. R.M. Clarke, P.L. Brink, B. Cabrera, P. Colling, M.B. Crisler , A.K. Davies, S. Eichblatt , R.J. Gaitskell , J. Hellmig , J.M. Martinis, S.W. Nam, T. Saab, and B.A. Young Enhanced ballistic phonon production for surface events in cryogenic silicon detectors, Appl. Phys. Lett. 76 (2000) 2958
3. D. Tovey, R. Gaitskell, P. Gondolo, Y. Ramachers, and L. Roszkowski, A New Method for Presenting Model-Independent Spin-Dependent Cross-Section Limits from Dark Matter Searches, Phys. Lett. B 488 (2000) 17
4. R Abusaidi et al. [CDMS Collaboration], Results on the WIMP–Nucleon Cross Section from the Cryogenic Dark Matter Search (CDMS), Phys. Rev. Lett. 84 (2000) 5699
5. C. E. Aalseth et al. Comment on "Evidence for Neutrinoless Double Beta Decay" Mod.Phys.Lett. A17 (2002) 1475-1478, (hep-ex/0202018)
6. D. Abrams et. al, (CDMS Collaboration) Exclusion Limits on the WIMP-Nucleon CrossSection from the Cryogenic Dark Matter Search Phys. Rev. D 66 , 122003 (2002), (astro–ph/0203500)
7. P.L. Brink et al., "Further results from the CDMS experiment" NIM A 520 (2004) 105-107.
8. D.A. Akerib et al. “First Results of the Silicon ZIP Detector, operated under elevated bias voltage”, NIM A520 (2004)
9. V. Mandic et al., "Study of the dead layer in germanium for the CDMS detectors", NIM A 520 (2004) 171-174.

10. C.L. Chang et al., "Installation and commissioning of the CDMSII experiment at Soudan", NIM A 520 (2004) 116-119.
11. D.S. Akerib et al. (CDMS Collaboration), "New results from the Cryogenic Dark Matter Search (CDMS) Experiment", Phys. Rev. D68 (2003) 082002, hep-ex/0306001.
12. D.S. Akerib et al. (CDMS Collaboration), " First Results from the Cryogenic Dark Matter Search in the Soudan Underground Lab', Phys. Rev. Lett 93 (2004) 211301, astro-ph/0405033.
13. D.S. Akerib, M. Dragowsky, D. Driscoll, S. Kamat, T. Perera, R. Schnee, G. Wang, R. Gaitskell, L. Bogdanova, V. Trofimov, ``Demonstration of feasibility of operating a silicon ZIP detector with 20 eV" threshold," NIM A520 163 (2004).
14. D. S. Akerib, et al. (CDMS Collaboration), "Exclusion Limits on the WIMP-Nucleon CrossSection from the First Run of the Cryogenic Dark Matter Search in the Soudan Underground Lab", Phys. Rev. D72 (2005) 052009, astro-ph/0507190.
15. D.S. Akerib et al. (CDMS Collaboration), "Limits on spin-independent WIMP-nucleon interactions from the two-tower run of the Cryogenic Dark Matter Search", Phys. Rev. Lett. 96 (2006) 011302, astro-ph/0509259.
16. D.S. Akerib et al. (CDMS Collaboration), "Limits on spin-dependent WIMP-nucleon interactions from the Cryogenic Dark Matter Search", Phys. Rev. D73 (2006) 011102, astroph/0509269.
17. E. Aprile ,C. E. Dahl, L. DeViveiros, R. Gaitskell, K. L. Giboni, J. Kwong, P. Majewski, K. Ni, T. Shutt and M. Yamashita, "Simultaneous Measurement of Ionization and Scintillation from Nuclear Recoils in Liquid Xenon as Target for a Dark Matter Experiment", Phys. Rev. Lett. 97 (2006) 081302, astro-ph/0601552.
18. M. J. Attisha, PhD Thesis, (April, 2006) Brown University. (Gaitskell, Advisor)
19. J. Angle et al., (XENON10 Collaboration), "First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory", Phys. Rev. Lett. 100, 021303 (2008) arxiv/0706.0039.
20. J. Angle et al., (XENON10 Collaboration), "The XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory", In preparation, for Nucl. Instr. and Meth. A (2008)
21. J. Angle et al., (XENON10 Collaboration), "Exclusion limits on spin-dependent WIMPnucleon cross-section from the XENON10 experiment Phys.Rev.Lett.101:091301,2008. arXiv:0805.2939 [astro-ph]
22. Z. Ahmed et al., (CDMS Collaboration), "A Search for WIMPs with the First Five-Tower Data from CDMS", arXiv:0802.3530 submitted to PRL (2008)
23. D.S. Akerib et al. (CDMS Collaboration). "Design and performance of a modular lowradioactivity readout system for cryogenic detectors in the CDMS experiment." Nucl.Instrum.Meth.A591:476-489,2008.
24. P. Sorensen et al. (XENON10 Collaboration). "Determination of the scintillation and ionization yield of liquid Xe from the XENON10 experiment." Submitted to Phys. Rev C, arXiv:0807.0459 [astro-ph]
25. D. S. Akerib, et al., "Data acquisition and readout system for the LUX dark matter experiment," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 668, pp. 1-8, 2012.
26. D. S. Akerib, et al., "An Ultra-Low Background PMT for Liquid Xenon Detectors," arXiv:1205.2272 [physics.ins-det], pp. 12, 2012.
27. D. S. Akerib, et al., "The LUX Prototype Detector", arXiv:1207.3665 [physics.ins-det], pp. 12, 2012
28. D. S. Akerib, et al., "Radio-assay of Titanium samples for the LUX Experiment", arXiv:1112.1376 [physics.ins-det], pp. 8, 2012

29. D. S. Akerib, et al., "LUXSim: A Component-Centric Approach to Low-Background Simulations," *Nuclear Instruments and Methods in Physics Research Section A*, vol. 675 , pp. 63 (2012)

CAMPBELL, JOE CHARLES
Lucian Carr Professor of Electrical and Computer Engineering

Joe C. Campbell received the B.S. Degree in Physics for the University of Texas at Austin in 1969, and the M.S. and Ph.D. degrees in Physics from the University of Illinois at Urbana-Champaign in 1971 and 1973, respectively. From 1974 to 1976 he was employed by Texas Instruments where he worked on integrated optics. In 1976 he joined the staff of AT&T Bell Laboratories in Holmdel, New Jersey. In the Crawford Hill Laboratory he worked on a variety of optoelectronic devices including semiconductor lasers, optical modulators, waveguide switches, photonic integrated circuits, and photodetectors with emphasis on high-speed avalanche photodiodes for high-bit-rate lightwave systems. In January of 1989 he joined the faculty of the University of Texas at Austin as Professor of Electrical and Computer Engineering and Cockrell Family Regents Chair in Engineering. In January of 2006, Professor Campbell moved to the University of Virginia in Charlottesville as the Lucian Carr Professor of Electrical and Computer Engineering.

Professor Campbell's technical area is photodetectors. At present he is actively involved in single-photon-counting APDs, Si-based optoelectronics, high-speed low-noise avalanche photodiodes, high-power high-linearity photodiodes, SiC ultraviolet photodetectors, and quantum-dot infrared imaging. To date he has coauthored seven book chapters, 340 articles for refereed technical journals, and more than 300 conference presentations. Professor Campbell teaches graduate and undergraduate courses on lasers and optoelectronic components. In 2002 Professor was inducted into the National Academy of Engineering.

Professional Experience
University of Virginia, Professor, January 2006 - present
University of Texas, Professor, January 1989 – December 2005
AT&T Bell Laboratories, Supervisor, 1985-1989
AT&T Bell Laboratories, Member of Technical Staff, 1976-1985
Texas Instruments, Member of Technical Staff, 1974-1976
University of Illinois, Post-Doctoral Fellow, 1973-1974

Honors
National Academy of Engineering (2002)
OSA/IEEE LEOS John Tyndall Award (2009)
International Symposium on Compound Semiconductors Quantum Device Award (2009)
IEEE Photonics Award (2008)
OSA Nicholas Holonyak Award (2003)
IEEE/LEOS William Streifer Scientific Achievement Award (2001)
IEEE Millennium Medal (2000)
Fellow of Optical Society of America (1998)
Fellow Member of IEEE (1990)
Fellow of American Physical Society (2003)
Fellow International Engineering Consortium (2008)
AT&T Bell Laboratories Distinguished Member of Technical Staff (1985)

Related references:

1. Xiaogang Bai, Han-Din Liu, Dion C. McIntosh, and Joe C. Campbell, "High-detectivity and high-single-photon-detection-efficiency 4H-SiC avalanche photodiodes," IEEE J. Quantum Electron, vol. 45, no. 3, pp. 300-3003, March 2009.
2. Dion McIntosh, Qiugui Zhou, Yaojia Chen, and Joe C. Campbell, "High quantum efficiency GaP avalanche photodiodes," Optics Express, vol. 19, no. 20, pp. 19607-19612, Sept. 26, 2011.
3. Qiugui Zhou, Dion McIntosh, Zhiwen Lu, Anand V. Sampath, Hongen Shen, and Michael Wraback, "GaN/SiC avalanche photodiodes," Appl. Phys. Lett., vol. 99, no. 13, 131110 , 2011.
4. Wenlu Sun, Xiaoguang Zheng, Zhiwen Lu, and Joe C. Campbell, "Monte Carlo simulation of $Al_xGa_{1-x}As$ (x0.6) avalanche photodiodes," IEEE J. Quantum Elect., vol. 47, no. 12, pp. 1531-1536, 2011.
5. Qiugui Zhou, Dion McIntosh, Yaojia Chen, Wenlu Sun, Zhi Li, and Joe C. Campbell, "Nanosphere natural lithography surface texturing as anti-reflective layer on SiC photodiodes," Optics Express, vol. 19, no. 24, pp. 23664-23670, Nov. 21, 2011.
6. Qiugui Zhou, Dion McIntosh, Han-Din Liu, and J. C. Campbell, "Proton-implantation-isolated separate absorption, charge, and multiplication 4H-SiC avalanche photodiodes," IEEE Photon. Tech. Lett., vol. 23, no. 5, pp. 200-301, 2011.
7. A. V. Sampath, Qiugui Zhou, R. Enck, C. S. Gallinat, P. Rotella, D. McIntosh, P. Shen, J. Campbell, and M. Wraback, "Impact of hetero-interface on the photoresponse of GaN/SiC separate absorption and multiplication avalanche photodiodes," 2011 International Semiconductor Device Research Symposium, 2 pp., ISBN-13: 978-1-4577-1755-0, 2011, (10.1109/ISDRS.2011.6135205).
8. Qiugui Zhou, Han-Din Liu, D. McIntosh, Chong Hu, and J. C. Campbell, "Simulation of Geiger mode silicon carbide avalanche photodiode," Proceedings 2010 10th International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD), pp. 111-112, 2010.
9. Mingguo Liu, Chong Hu, Xiaogang Bai, Joe C. Campbell, Zhong Pan, and M. M. Tashima, "High-performance InGaAs/InP single-photon avalanche photodiode," IEEE J. Selected Topics on Quantum Electron., vol. 13, no. 4, pp. 887-893, July/Aug 2007.
10. Mingguo Liu, Chong Hu, Joe C. Campbell, Zhong Pan, and Mark M. Tashima, "A novel quenching circuit to reduce afterpulsing of single photon avalanche diodes," IEEE Journal of Quantum Electronics, vol. 44, no. 5, pp. 430-434, May 2008.
11. Chong Hu and Joe C. Campbell, "Infrared single photon avalanche detectors," Phys. Status Solidi, vol. C7, no. 10, pp. 2536-2539, 2010.
12. Chong Hu, Xiaoguang Zheng, Joe C. Campbell, Bora M. Onat, Xudong Jiang, and Mark A. Itzler, "Characterization of an InGaAs/InP-based single-photon avalanche diode with gated-passive quenching with active reset circuit," J. Modern Optics, vol. 58, Nos. 3-4, pp. 201-209, February 2011.

SUPPORT REPORT FOR JIM CHRISTIAN

Active Support

(C12-40) HDTRA1-12-C-0045 3/13/2012 to 3/12/2015
DTRA PI: Jaroslaw Glodo $2,399,996 5.4 Mo.
Gamma-Neutron Imaging System
Recent development of Cs2LiYCl6:Ce (CLYC) provides an ideal material for dual mode detectors. CLYC offers (1) efficient thermal neutron detection; (2) excellent separation between gamma and neutron particles (>10-6); and (3) gamma-ray energy resolution as good as 4% at 662 keV. The goal of this effort is to use CLYC in combination with RMD's existing spectroscopic imaging technology (RadCamTM) to construct a dual gamma and neutron imaging system.The existing RadCamTM model will be modified to accommodate CLYC. Detection of gamma and neutron radiation will be tested. New apertures capable of handling gammas and neutrons will be designed and tested.

(C12-53) FA9453 12 C 0121 7/18/2012 to 7/17/2014
DOD-AF PI: James Christian $749,999 2.4 Mo.
Severe Space Weather Satellite Protection
Existing compact charged-particle detectors for satellites, such as the Teledyne Micro-dosimeter, provide dose and dose rate information; however, these devices do not discriminate between electron and proton events, do not provide spectroscopic information, and may have a limited radiation tolerance. The proposed solution involves expanding on Phase I results for coupling Diphenylanthracene (DPA) with a solid-state photomultiplier (SSPM) photodetector and developing the complementary readout circuitry required to detect/discriminate fast electrons from protons while providing dose and dose rate information characteristic of solar events over a wide range of energies.

(C11-46) HDTRA1-11-1-0028 5/1/2011 to 4/30/2014
DOD-DTRA PI: Erik Johnson $1,049,986 0.72 Mo.
WHITE PAPER Li-Ion Batteries for Forensic Neutron Dosimetry
Lithium-ion batteries are the common technology for powering portable electronics. The base element of lithium has a large cross section for thermal neutron capture. A common method for recording dose from radiation is to use a thermolumenescent dosimeter (TLD), which is based on a film of lithium fluoride. The research done under this program will investigate the potential for lithium-ion batteries as a dosimeter.

(C12-43) ALION 1216413 4/15/2012 to 8/15/2013
DTRA PI: James Christian $749,999 0.64Mo.
Multidisciplined Research in Nuclear Detection - REAL TIME DOSIMETER-
Subcontract to Alion The Prime Contract # DTRA01-02-D-0067. Alion IDIQ The objective of the proposed research and development plan is for RMD to complete the development of a Secondary *#SUB1216413.*Dosimeter and have that device NVLAP tested and certified. A second objective will be to prototype a Primary Dosimeter and conduct initial testing of that device at two independent facilities.

(C12-22) DE-SC0004367 8/15/2011 to 8/14/2013
DOE PI: Purushottam Dokhale $999,998 1.2 Mo.
Novel Concept in PET Imaging
The goal of the proposed project is to use of continuous crystals coupled to a new photodetector technology, silicon photomultiplier (SiPM) for investigating PET modules that are suitable for plant imaging studies, dedicated organ imaging systems as well as eventually clinical imaging. The main innovation of the proposed detector design over previously investigated continuous detectors is its ability to achieve high sensitivity and high spatial resolution in a thick continuous detector. High performance and low cost are expected from the proposed detector design.

(C12-08) NNX11CA24C 6/1/2011 to 5/31/2013
NASA PI: James Christian $599,993 2.4 Mo.
Fast Neutron Dosimeter for the Space Environment
The goal of the project is to develop a modular, compact, lightweight dosimeter that optimizes the use of detector material for secondary neutrons from space radiation.

(C12-44) ALION 1216413 4/15/2012 to 4/14/2013
DTRA PI: James Christian $439,997 .24 Mo.
Multidisciplined Research in Nuclear Detection - Solid State Photomultiplier (SSPM). The Prime Contract #DTRA01-02-D-0067. ALION IDIQ#SUB1216413
The objective of the proposed research and development plan is for RMD to conduct research on solid-state devices to replace current photomultipliers. RMD shall design and construct prototypes solid state photomultipliers (SSPM) fabricated with CMOS. RMD shall investigate improved technologies and methods for coupling SSPM devices to appropriate gamma/neutron scintillaotors. RMD shall construct and evaluate prototype detectors based on SSPM devices. RMD shall conduct studies of gamma and neutron scintillators and their potential for intergration with SSPM technologies.

Pending Support

(P13-018) Expected Start Date: 09/01/2013
NIH PI: Vivek Nagarkar $3,499,300 7.68Mo.
Photon Counting Detector for Dose Reduction in Whole Body CT
The goal of the proposed research is to develop a novel, cost-effective, high-resolution, X-ray photon counting detector suitable for whole body CT. This detector classifies photons of interest so efficiently and effectively that a CT scanner can operate at much higher levels of functionality and performance with reduced radiation dose to patients. Thus it will have significant impact on general population radiation exposure due to the current widespread use of CT. We therefore believe that it is in keeping with the National Institute of Biomedical Imaging and Bioengineering's mission.

(P13-015) S1.09-9261 Expected Start Date: 5/01/2013
NASA PI: James Christian $699,701 3.12 Mo.
Next Generation Gamma/Neutron Detectors for Planetary Science
Gamma-ray and neutron spectroscopy are well established techniques for determining the chemical composition of planetary surfaces, and small cosmic bodies such as asteroids and comets; however, new technologies with the potential to significantly improve the performance of planetary nuclear spectroscopy are emerging. We propose to develop new gamma-ray and neutron detectors based on wide-band-gap (WBG) solid-state photomultiplier (SSPM) photodetectors coupled to emerging scintillation materials such as Cs2YLiCl6:Ce (CLYC), and CeBr3 for gamma and neutron spectroscopic studies of planet surfaces and small cosmic bodies. The proposed SSPM photodetector for scintillation readout is based on AlGaAs, a WBG compound semiconductor with aluminum concentration of 60% to 90%. The ~2-eV band-gap energy of this material is engineered to match the emission spectrum of both CLYC and CeBr3.
The high band-gap of AlGaAs also provides much lower dark noise and better radiation tolerance than Si-based detectors. Compared to conventional PMTs, the compact size, low voltage operation, and lighter weight of AlGaAs SSPM is ideal for spaced-based instruments. The advantages of AlGaAs SSPMs and the excellent detection properties of CLYC and CeBr3 scintillation materials make them a perfect match in the development of new gamma and neutron spectrometers for planetary science.

(P13-006) Expected Start Date: 4/1/2013
NIH PI: James Christian $199,834 0.48 Mo.
Small Animal SPECT Detector for Dual Modality SPECT-MRI Imaging
The goal of the research effort is to develop a high-performance, modular SPECT camera insert that can achieve unprecedented spatial resolution and sensitivity for small-animal studies, and can be simultaneously operated within the bore of a magnetic resonance imaging instrument. In order to study the dynamics of the heart in small animal models such as mice, a high-performance, dual-mode, simultaneous SPECT-MR imaging system is required. Current commercial systems provide a singular image type: SPECT systems provide a <1–mm image of physiology, while existing MRI systems provide high-spatial resolution, high-contrast images of morphology. The spatial resolution of SPECT cameras is limited by parallax, due to the finite thickness of the detector material, the range of the photoelectron in the detector, and the signal-to-noise performance. Detector materials with a high stopping power, such as emerging scintillation materials used in our modular SPECT camera, can optimize the spatial resolution performance.

\OVERLAP: There is no scientific or budgetary overlap between the application and the programs above.

SUPPORT REPORT FOR XIAOJIE CHEN

Active Support

(C12-53) FA9453 12 C 0121 7/18/2012 to 7/17/2014
DOD-AF PI: James Christian $749,999 1.92 Mo.
Severe Space Weather Satellite Protection
Existing compact charged-particle detectors for satellites, such as the Teledyne Micro-dosimeter, provide dose and dose rate information; however, these devices do not discriminate between electron and proton events, do not provide spectroscopic information, and may have a limited radiation tolerance. The proposed solution involves expanding on Phase I results for coupling Diphenylanthracene (DPA) with a solid-state photomultiplier (SSPM) photodetector and developing the complementary readout circuitry required to detect/discriminate fast electrons from protons while providing dose and dose rate information characteristic of solar events over a wide range of energies.

(C11-46) HDTRA1-11-1-0028 5/1/2011 to 4/30/2014
DOD-DTRA PI: Erik Johnson $1,049,986 2.88 Mo.
WHITE PAPER Li-Ion Batteries for Forensic Neutron Dosimetry
Lithium-ion batteries are the common technology for powering portable electronics. The base element of lithium has a large cross section for thermal neutron capture. A common method for recording dose from radiation is to use a thermolumenescent dosimeter (TLD), which is based on a film of lithium fluoride. The research done under this program will investigate the potential for lithium-ion batteries as a dosimeter.

(C12-44) ALION 1216413 4/15/2012 to 4/14/2013
DTRA PI: James Christian $439,997 0.48 Mo.
*Multidisciplined Research in Nuclear Detection - Solid State Photomultiplier (SSPM). The Prime Contract #DTRA01-02-D-0067. ALION IDIQ#SUB1216413.*The objective of the proposed research and development plan is for RMD to conduct research on solid-state devices to replace current photomultipliers. RMD shall design and construct prototypes solid state photomultipliers (SSPM) fabricated with CMOS. RMD shall investigate improved technologies and methods for coupling SSPM devices to appropriate gamma/neutron scintillaotors. RMD shall construct and evaluate prototype detectors based on SSPM devices. RMD shall conduct studies of gamma and neutron scintillators and their potential for intergration with SSPM technologies.

Pending Support

(P13-015) S1.09-9261 Expected Start Date: 5/01/2013
NASA PI: James Christian $699,701 4.08 Mo.
Next Generation Gamma/Neutron Detectors for Planetary Science
Gamma-ray and neutron spectroscopy are well established techniques for determining the chemical composition of planetary surfaces, and small cosmic bodies such as asteroids and comets; however, new technologies with the potential to significantly improve the performance of planetary nuclear spectroscopy are emerging. We propose to develop new gamma-ray and neutron detectors based on wide-band-gap (WBG) solid-state photomultiplier (SSPM) photodetectors coupled to emerging scintillation materials such as Cs2YLiCl6:Ce (CLYC), and CeBr3 for gamma and neutron spectroscopic studies of planet surfaces and small cosmic bodies. The proposed SSPM photodetector for scintillation readout is based on AlGaAs, a WBG compound semiconductor with aluminum concentration of 60% to 90%.The ~2-eV band-gap energy of this material is engineered to match the emission spectrum of both CLYC and CeBr3. The high band-gap of AlGaAs also provides much lower dark noise and better radiation tolerance than Si-based detectors. Compared to conventional PMTs, the compact size, low voltage operation, and lighter weight of AlGaAs SSPM is ideal for spaced-based instruments. The advantages of AlGaAs SSPMs and the excellent detection properties of CLYC and CeBr3 scintillation materials make them a perfect match in the development of new gamma and neutron spectrometers for planetary science.

(P13-006) Expected Start Date: 4/1/2013
NIH PI: James Christian $199,834 0.24 Mo.
Small Animal SPECT Detector for Dual Modality SPECT-MRI Imaging
The goal of the research effort is to develop a high-performance, modular SPECT camera insert that can achieve unprecedented spatial resolution and sensitivity for small-animal studies, and can be

simultaneously operated within the bore of a magnetic resonance imaging instrument. In order to study the dynamics of the heart in small animal models such as mice, a high-performance, dual-mode, simultaneous SPECT-MR imaging system is required. Current commercial systems provide a singular image type: SPECT systems provide a <1–mm image of physiology, while existing MRI systems provide high-spatial resolution, high-contrast images of morphology. The spatial resolution of SPECT cameras is limited by parallax, due to the finite thickness of the detector material, the range of the photoelectron in the detector, and the signal-to-noise performance. Detector materials with a high stopping power, such as emerging scintillation materials used in our modular SPECT camera, can optimize the spatial resolution performance.

OVERLAP: There is no scientific or budgetary overlap between the application and the programs above.

BIOGRAPHICAL SKETCH – Erik Bjorn Johnson, Ph.D.
Senior Scientist, Instrument Research and Development Group

Education and Training:

University of Rochester	B.S.	1997	Physics
University of Rochester	M.S.	1999	Physics
University of Rochester	Ph.D.	2003	High Energy Nuclear Physics
University of Kansas	Post-Doc	2006	High Energy Nuclear Physics

Research and Professional Experience:

Dr. Johnson, a native of South Florida, completed his BS in Physics at the University of Rochester (UofR) as a Bausch and Lomb Scholar. He obtained his MS in 1999, and he completed his Ph.D. in 2003 on the development and application of the Phobos Time-of-Flight Wall at the Relativistic Heavy-Ion Collider (RHIC). The work he completed with the Phobos collaboration included building various timing detectors and support equipment for maintaining and calibrating the system. Dr. Johnson continued to study relativistic heavy-ion physics with the BRAHMS experiment at RHIC as a post-doctoral researcher at the University of Kansas.

In September 2006, Dr. Johnson joined Radiation Monitoring Devices, Inc. (RMD) to work in the Instrument Research and Development Group. His current interests are focused on the development of novel devices using avalanche photodiodes built using CMOS technology in arrays called solid-state photomultipliers (SSPM) for scientific, military, and medical fields. Dr. Johnson's help contribute to further development of this technology for improving dark noise and detection efficiency. Various instruments and prototypes have been developed using this technology, which include calorimeters, dosimeters for space and terrestrial applications, and radiation monitors. The research programs Dr. Johnson has been involved with include developing devices for charged particles, gamma rays, electrons, charged mesons, and gamma rays. As the demand for neutron detectors have increased, the work effort within this scope has increased, and Dr. Johnson is contributing to multiple neutron detector systems for space applications, which are either design to determine human equivalent dose or spectral information. The other types of research Dr. Johnson is conducting includes the development of a CMOS APD that can operate in cryogenic temperatures down to 4 K and nuclear forensics involving using lithium batteries to determine the neutron spectrum from a nuclear event. The CMOS cryogenic APD work developed a compact, completely packaged device, which has shown some interests outside the primary research group for which the device was developed. The research on nuclear forensic using lithium batteries has recently begun, and Dr. Johnson is the principal investigator for the work.

Selected Peer-reviewed Publications

1. **E. B. Johnson**, C. Whitney, X. J. Chen, C. J. Stapels, K. E. Holbert, A. Kaczmarowski, T. Stannard, and J. F. Christian, " Li-Ion Batteries Used as Ubiquitous Neutron Sensors for Nuclear Forensics", IEEE Transactions on Nuclear Science, under review.
2. **E. B. Johnson**, X. J. Chen, C. J. Stapels, C. Whitney and J. F. Christian, "High performance geiger photodiodes in a 0.18-um feature size CMOS technology", IEEE Nuclear Science Symposium 1660-1664 (2011).
3. **E. B. Johnson**, C. J. Stapels, X. J. Chen, C. Whitney, E. C. Chapman, G. Alberghini, R. Rines, F. Augustine, R. Miskimen, D. Lydon, and J. Christian, "CMOS Solid-State Photomultipliers for High Energy Resolution Calorimeters," SPIE Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XIII 8142, 81420M 1-14 (2011)
4. **E. B. Johnson**, C. J. Stapels, X. J. Chen, C. Whitney, E. C. Chapman, G. Alberghini, R. Rines, F. Augustine and J. Christian, "CMOS Solid State Photomultipliers for Ultra-Low Light Levels", SPIE Advanced Photon Counting Techniques V 8033, 80330R 1-22 (2011).

5. **E. B. Johnson**, E. Chapman, X. J. Chen, S. Mukhopadhyay, C. J. Stapels, J. F. Christian and E. Benton, "Performance characteristics of the CMOS SSPM tissue-equivalent space dosimeter", IEEE Aerospace Conference 2010, 1-8 (2010).
6. **E. B. Johnson,** C. J. Stapels, X. Jie Chen, F. L. Augustine, and J. F. Christian, "Large-area CMOS solid-state photomultipliers and recent developments," Nuclear Instruments and Methods in Physics Research Section A: (SORMA) XII 2010, vol. 652, pp. 494-499, 2011
7. **E. B. Johnson**, P. Barton, K. Shah, C. J. Stapels, D. K. Wehe and J. F. Christian, "Energy Resolution in CMOS SSPM Detectors Coupled to an LYSO Scintillator", IEEE Transactions on Nuclear Science, 56 (3), 1024-1032 (2009).
8. **E. B. Johnson**, E. Chapman, P. Linsay, S. Mukhopadhyay, C. J. Stapels, J. F. Christian and E. Benton, "Tissue-Equivalent Solar Particle Dosimeter using CMOS SSPMs", IEEE Aerospace Conference 2009, 1-7 (2009).
9. **E. B. Johnson**, X. J. Chen, R. Miskimen, D. Von Maluski, C. J. Stapels, S. Mukhopadhyay, F. Augustine and J. F. Christian, "Characteristics of CMOS Avalanche Photodiodes at Cryogenic Temperatures", IEEE Nuclear Science Symposium, 2108-2114 (2009).
10. **E. B. Johnson**, C. Stapels, J. Glodo, S. Mukhopadhyay, P. Linsay, K. Shah, P. Barton, D. Wehe, E. Benton and S. Augustine, "Radiation Measurements using Solid-State Photomultipliers:Gammas, Charged Particles, and Neutrons", IEEE Nuclear Science Symposium, 2997 - 3001 (2008).
11. **E. B. Johnson**, C. J. Stapels, M. McClish, S. Mukhopadhyay, P. Linsay, K. Shah, P. Barton, D. Wehe, S. Augustine and J. F. Christian, "New Developments for CMOS SSPMs", IEEE Nuclear Science Symposium, 1516 - 1522 (2008).
12. **E. B. Johnson**, "Rapidity Dependence of Elliptic Flow at RHIC", Particles and Nuclei International Conference 2005 842, 137-139 (2006)**.**

<u>Synergistic Activities:</u>

1. Presentation: “Li-Ion Batteries Used for Ubiquitous Neutron Sensors for Nuclear Forensics”, SORMA West, Oakland, CA, May 2012
2. Presentation: “Performance Characteristics of the Next Generation Solid-State Photomultipliers”, DNP Conference, East Lansing, MI, October 2011
3. Presentation: “CMOS Solid-State Photomultipliers for High Energy Resolution Calorimeters”, SPIE optical Engineering and Applications, San Diego, CA, August 2011
4. Presentation: “Advances in Scientific Instrumentation at RMD”, Talk at the University of Kansas, Lawrence, KS 2011
5. Presentation: “Performance Characteristics of a Large-Area CMOS Solid-State Photomultiplier for Radiation Detectors”, IRRMA, Kansas City, MO, June 2011
6. Presentation: “CMOS Solid-State Photomultipliers for Ultra-Low Light Levels”, SPIE Defense, Security and Sensing Symposium, Orlando, FL, April 2011
7. Presentation: “Solid-State Photomultipliers for the PRIMEX Calorimeter”, Workshop on Advances of Nuclear Detector, Rutgers University, January 2011
8. Presentation: “The Properties of Cryogenic CMOS Avalanche Photodiodes”, DNP Conference, Santa Fe, NM, October 2010
9. Poster: “The Properties of Cryogenic CMOS Avalanche Photodiodes”, SORMA, Ann Arbor, MI, May 2010
10. Presentation: “Large-Area CMOS Solid-State Photomultipliers and Recent Developments”, SORMA, Ann Arbor, MI, May 2010
11. IEEE Member
12. American Physical Society Member
13. Reviewed paper for IEEE Transactions on Nuclear Science, Nuclear Instruments and Methods Section A, and IEEE Transactions on Instrumentation & Measurement

SUPPORT REPORT FOR ERIC JOHNSON

Active Support

(C12-40) HDTRA1-12-C-0045 3/13/2012 to 3/12/2015

DTRA	PI: Jaroslaw Glodo	$2,399,996	6.54 Mo.

Gamma-Neutron Imaging System

Recent development of Cs2LiYCl6:Ce (CLYC) provides an ideal material for dual mode detectors. CLYC offers (1) efficient thermal neutron detection; (2) excellent separation between gamma and neutron particles (>10-6); and (3) gamma-ray energy resolution as good as 4% at 662 keV. The goal of this effort is to use CLYC in combination with RMD's existing spectroscopic imaging technology (RadCamTM) to construct a dual gamma and neutron imaging system. The existing RadCamTM model will be modified to accommodate CLYC. Detection of gamma and neutron radiation will be tested. New apertures capable of handling gammas and neutrons will be designed and tested.

(C12-53) FA9453 12 C 0121 7/18/2012 to 7/17/2014

DOD-AF	PI: James Christian	$749,999	1.92 Mo.

Severe Space Weather Satellite Protection

Existing compact charged-particle detectors for satellites, such as the Teledyne Micro-dosimeter, provide dose and dose rate information; however, these devices do not discriminate between electron and proton events, do not provide spectroscopic information, and may have a limited radiation tolerance. The proposed solution involves expanding on Phase I results for coupling Diphenylanthracene (DPA) with a solid-state photomultiplier (SSPM) photodetector and developing the complementary readout circuitry required to detect/discriminate fast electrons from protons while providing dose and dose rate information characteristic of solar events over a wide range of energies.

(C11-46) HDTRA1-11-1-0028 5/1/2011 to 4/30/2014

DOD-DTRA	PI: Erik Johnson	$1,049,986	3.6 Mo.

WHITE PAPER Li-Ion Batteries for Forensic Neutron Dosimetry

Lithium-ion batteries are the common technology for powering portable electronics. The base element of lithium has a large cross section for thermal neutron capture. A common method for recording dose from radiation is to use a thermolumenescent dosimeter (TLD), which is based on a film of lithium fluoride. The research done under this program will investigate the potential for lithium-ion batteries as a dosimeter.

(C12-22) DE-SC0004367 8/15/2011 to 8/14/2013

DOE	PI: Purushottam Dokhale	$999,998	2.4 Mo.

Novel Concept in PET Imaging

The goal of the proposed project is to use of continuous crystals coupled to a new photodetector technology, silicon photomultiplier (SiPM) for investigating PET modules that are suitable for plant imaging studies, dedicated organ imaging systems as well as eventually clinical imaging. The main innovation of the proposed detector design over previously investigated continuous detectors is its ability to achieve high sensitivity and high spatial resolution in a thick continuous detector. High performance and low cost are expected from the proposed detector design.

(C12-08) NNX11CA24C 6/1/2011 to 5/31/2013

NASA	PI: James Christian	$599,993	2.4 Mo.

Fast Neutron Dosimeter for the Space Environment

The goal of the project is to develop a modular, compact, lightweight dosimeter that optimizes the use of detector material for secondary neutrons from space radiation.

(C12-44) ALION 1216413 4/15/2012 to 4/14/2013

DTRA	PI: James Christian	$439,997	0.48Mo.

Multidisciplined Research in Nuclear Detection - Solid State Photomultiplier (SSPM). The Prime Contract #DTRA01-02-D-0067. ALION IDIQ#SUB1216413.

The objective of the proposed research and development plan is for RMD to conduct research on solid-state devices to replace current photomultipliers. RMD shall design and construct prototypes solid state photomultipliers (SSPM) fabricated with CMOS. RMD shall investigate improved technologies and methods for coupling SSPM devices to appropriate gamma/neutron scintillaotors. RMD shall construct and evaluate prototype detectors based on SSPM devices. RMD shall conduct studies of gamma and neutron scintillators and their potential for intergration with SSPM technologies.

(C12-51) DE-SC0008292 6/28/2012 to 3/27/2013
DOE PI: Kanai Shah $149,999 0.72 Mo.
Solid-State Neutron Detector for Nuclear Material Accounting
Based on Cs2LiYCl6:Ce (CLYC) crystalline scintillator technology developed at RMD and state-of-the-art photodetector technologies, we propose to develop a solid-state neutron detector that replaces He-3 tubes and provides spectral information. CLYC provides high intrinsic detection efficiency for thermal neutrons comparable to (or higher than) He-3 tubes, and being a scintillation material, the kinetic energy transferred to the material will produce a light flash dependent on the type of radiation (i.e. gamma rays generate an unambiguous pulse shape compared to neutron events).

(C10-41) 1R44NS066521-01A1 3/15/2010 to 2/28/2013
NIH PI: Gerald Entine $1,398,636 3.24 Mo.
Simultaneous PET-MR Small Animal Imaging
The proposed research will investigate a promising detector technology which should have a major impact in health care, in particular, in the development of detectors for invivo imaging. Other areas to which this research could be of benefit are: physics research, materials studies, homeland defense, and non-destructive testing.

Pending Support

(P13-015) S1.09-9261 Expected Start Date: 5/01/2013
NASA PI: James Christian $699,701 1.92 Mo.
Next Generation Gamma/Neutron Detectors for Planetary Science
Gamma-ray and neutron spectroscopy are well established techniques for determining the chemical composition of planetary surfaces, and small cosmic bodies such as asteroids and comets; however, new technologies with the potential to significantly improve the performance of planetary nuclear spectroscopy are emerging. We propose to develop new gamma-ray and neutron detectors based on wide-band-gap (WBG) solid-state photomultiplier (SSPM) photodetectors coupled to emerging scintillation materials such as Cs2YLiCl6:Ce (CLYC), and CeBr3 for gamma and neutron spectroscopic studies of planet surfaces and small cosmic bodies. The proposed SSPM photodetector for scintillation readout is based on AlGaAs, a WBG compound semiconductor with aluminum concentration of 60% to 90%. The ~2-eV band-gap energy of this material is engineered to match the emission spectrum of both CLYC and CeBr3. The high band-gap of AlGaAs also provides much lower dark noise and better radiation tolerance than Si-based
detectors. Compared to conventional PMTs, the compact size, low voltage operation, and lighter weight of AlGaAs SSPM is ideal for spaced-based instruments. The advantages of AlGaAs SSPMs and the excellent detection properties of CLYC and CeBr3 scintillation materials make them a perfect match in the development of new gamma and neutron spectrometers for planetary science.

OVERLAP: There is no scientific or budgetary overlap between the application and the programs above.

ADMINISTRATIVE REVIEW WORKSHEET

Rev June 2011

SBIR/STTR LEVEL OF EFFORT WORKSHEET

Company Name

Total Amount: 149999

	Small Business	Research Institution	Third Party	Exclusions
SMALL BUSINESS LEVEL OF EFFORT				
Total Salary, Wages and Fringe Benefits (A + B)	21798			
Section D, Travel	3386			
Section F2 - Publication Costs	0			
Section F6 - Facility Rental/User Fee	0			
Section F8, F9, F10 - Other*	0			
*Determine whether charges should be charged to the small business, RI, or Third Party				
Section H - Indirect Costs	65121			
Section J - Fee	9813			
RESEARCH INSTITUTION LEVEL OF EFFORT (STTR ONLY or BOTH)				
Section 5 - Subaward [Total Amount Requested by RI - Materials/Supplies, Equipment, etc.] Use RI Budget justification.				
THIRD PARTY LEVEL OF EFFORT				
Section F3 - Consultant Services			4500	
Section F4 - ADP/Computer Services			0	
Section F5 - Subaward			38200	
Section F8, F9, F10 - Other*			0	
*Determine whether charges should be charged to the small business, RI, or Third Party				
EXCLUSIONS				
Section C - Equipment				0
Equipment Costs included RI or Subaward Budget				0
TOTAL				**0**
Section F1 - Materials and Supplies				7181
Materials and Supplies included RI or Subaward Budget				0
TOTAL				**7181**
Section F6 - Equipment Rental				0
Equipment Rental included RI or Subaward Budget				0
TOTAL				**0**
Section F8, F9, F10 - Other (Determine whether charges should be charged to the small business, RI, or Third Party)				0
Other Exclusion Costs included in RI or Subaward Budget				0
TOTAL				**0**
TOTAL	**100118**	**0**	**42700**	**7181**

SPREADSHEET ACCURACY CHECK

Total Analytical Effort (Total - Exclusions)

142818

Total Analytical Effort (Small Business + RI + Third Party)

142818

Above numbers should match. If they don't something is incorrect on your spreadsheet

	Small Business	Research Institution	Third Party
LEVEL OF EFFORT	**70%**	**0%**	**30%**
SBIR Only Requirements	**50%**		
STTR Only Requirements	**40%**	**30%**	
Both SBIR & STTR Requirements			

Prof Richard Gaitskell

Dept of Physics
Brown University
Box 1843
Providence, RI 02912
USA

Direct line +1 (401) 863 9783
Local fax +1 (401) 863 2024
E-mail gaitskell@brown.edu

October 5, 2012

RE:– LOW NOISE SOLID STATE PHOTOMULTIPLIER FOR DARK MATTER SEARCHES

Dear Sir or Madam,

This letter confirms our intention to make available personnel and also equipment belonging to my Particle Astrophysics Group at Brown University in order to carry out the Group's responsibilities under the sub-award in the DOE SBIR-STTR FY 2013 Funding Opportunity Announcement DE-FOA-000760.

The group will be responsible for studies under R&D related to the development of a low noise solid state photomultiplier for dark matter searches using liquid xenon targets.

The graduate student, for which salary support is requested in the proposal, will work on the above tasks as stated in the proposal and letter of intent. Equipment that has previously been purchased will also be used in the above work.

Yours sincerely,

Richard Gaitskell

Rick Gaitskell , Professor, Dept. of Physics, Brown University

Jeremy Chapman

Jeremy Chapman, Graduate Student, Dept. of Physics, Brown University

UNIVERSITY of VIRGINIA
ENGINEERING

Charles L. Brown Department of
Electrical & Computer Engineering

August 27, 2010

Dr. Erik Johnson
Radiation Monitoring Devices, Inc.
44 Hunt Street
Watertown, MA 02472

Dear Dr. Johnson:

I am writing this letter to indicate my commitment for your project titled "Low-Noise Solid-State Photomultiplier for Dark Matter Searches". As you know, low-level radiation detectors typically employ a photomultiplier tube (PMT). While PMTs have achieved excellent performance, they have numerous disadvantages including high cost and kV-level bias requirements. In addition they are bulky, fragile, and can be destroyed by ambient light. My group at the University of Virginia has been studying wide-bandgap avalanche photodiodes (APDs) as possible replacements for PMTs. In this program we will assist Radiation Monitoring Devices in the development of avalanche photodiodes that operate in the deep ultraviolet.

The following is our proposed work plan:
Task 1: Establish design specifications
Task 2: Identify candidate semiconductor materials for deep UV Geiger-mode avalanche photodiodes
Task 3: Design deep UV Geiger-mode avalanche photodiodes
Task 4: Simulation of deep UV Geiger-mode avalanche photodiodes
Task 5: Procure materials and process wafer
Task 6: Write Phase-I reports and Phase-II proposal

Phase I of this program will be done as a subcontract with a total budget of $20,350.07.

Sincerely,

Joe C. Campbell

Joe C. Campbell
Lucien Carr Professor Electrical and Computer Engineering

September 27, 2012

Dr. Erik Johnson
Radiation Monitoring Devices, Inc.
44 Hunt Street
Watertown, MA 02472

Dear Dr. Johnson:

Thank you for the invitation to work with you on your project titled “Low-Noise Solid-State Photomultiplier for Dark Matter Searches”. As a consultant, I anticipate providing expertise on the materials and device considerations of ultraviolet avalanche photodiodes. Recently, my group at the University of Virginia has developed high-performance avalanche photodiodes that operate in the ultra-violet spectral regime. We anticipate that we will extend that work to shorter wavelengths in the proposed program.

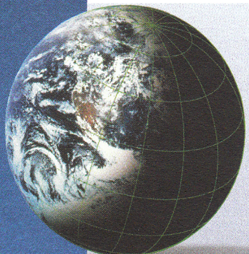
My consulting rate is $125 per hour. I estimate that the Phase I project (first 10 months) will necessitate a commitment of 36 hours.

Your clear commitment to completing the science and developing of this important technology is very important to me, since only that way will society benefit from these breakthrough ideas.

Sincerely,

Joe C. Campbell

Joe C. Campbell
Lucien Carr Professor Electrical and Computer Engineering



Market Opportunity

RMD is developing a new solid-state photomultiplier for dark matter studies. Our approach uses either a high-quality 4H-SiC epitaxial wafers or advanced processing techniques for silicon. In either case, the goal is to significantly reduce the dark current by at least an order or magnitude and increase the detection efficiency up to ane beyond 100% for 175 nm photons compared to existing silicon-based devices. Our goal is to integrate this new SSPM into a liquid Xenon dark matter detector system.

Dark matter detectors require robust, low-noise, high efficiency photodetectors. Photomultiplier tubes (PMT) are currently the photon detector of choice, primarily because of its low noise performance. The dark current per unit area of sensitivity associated with PMT's operation is difficult to match with other types of detectors. However, PMTs are limited in that they are bulky, require high voltage, and are susceptible to large magnetic fields and helium.

The alternative to the photomultiplier tube is the solid-state photomultiplier (SSPM). Solid-state photomultiplier consists of an array of photodiodes operating in Geiger mode and have the potential to supplant PMTs for detector systems because they:

- use less material (radioactive background is suppressed),
- can achieve higher quantum efficiencies over a broader spectral range,
- use small operating bias,
- insensitive to magnetic fields or other environmental conditions,
- are fabricated in a more cost effective manner,
- can obtain a rise time similar to a PMT,
- provide an excess noise comparable to a PMT, and
- allow for on-chip circuitry.

RMD see SSPMs as a viable alternative to traditional PMTs for a number of applications, including:

1. Advanced radiation detectors, including PET and SPECT imagers
2. Dosimeters
3. Radiation imaging cameras
4. Ultra-fast optical digital cameras
5. Optical tomography photodetectors
6. Position-sensitive photodetectors
7. Optical telecommunication sensors
8. Spectrometry
9. X-ray cameras
10. Radioluminscent assays
11. Flow cytometry
12. DNA sequencers.

These applications represent substantial markets for SSPMs. In each of these markets SSPMs could be a truly disruptive technology, providing users with capabilities not available today.

The light detector market is very large and growing. Industry leader Hamamatsu stated that annual sales annual sales were up 30 percent over 2010. Furthermore, sales in their Electron Tube division and their Opto-semiconductor division represented

$570 Million and $562 Million respectively. These two division sales represent $1.132 Billion or 85 percent of Hamamatsu total sales.[1] Therefore the overall market for our SSPMs is clearly in excess of $1 Billion annually.

Additionally, Research organization, NanoMarkets stated that the global market for radiation detection materials was $1.5 Billion in 2011 and forecasts it to be $2.7 Billion by 2016 with an associated compound annual growth rate of 10%.[2] This is another clear sign that the potential for our SSPM's are very strong if our research is successful.

RMD estimates sales revenue of $95,000,000 and licensing revenue of $10,000,000 during the first 10 years of commercialization, based on the size and the potential of the photomultiplier market and the strength of the overall radiation detection materials market.

Intellectual Property Protection

RMD utilizes IP policies and procedures to document our research and avoid public disclosure until patent applications are been filed. We employ Wolf Greenfield (Boston, Mass); and Wilson Sonsini Goodrich & Rosati, (Seattle, WA) law firms specializing in intellectual property to help us obtain maximum protection for our intellectual property. RMD currently has 43 issued patents and 55 applications under review.

RMD has a strong portfolio of awarded patents as well as applications in this area. The following are three patents that RMD has been awarded:

1. Large Area Semiconductor Detector with Internal Gain, 7268339 US, 9/11/2007, Shah, et al.
2. Position Sensitive Solid State Detector with Internal Gain, 6781133 US, 8/24/2004, Shah, et al.
3. Position Sensitive Solid State Detector with Internal Gain, 6998619 US, 2/14/2006, Shah, et al.

The following are two applications that RMD has submitted to the USPTO:

1. Solid State Photomultiplier Using Buried P-N Junction, 61/549,958, 10/21/2011, Christian, et al.
2. Solid State Photomultiplier Using Wide Band Gap Materials, 61/533,632, 10/25/2011, Christian, et al.

Company/Team Information

Radiation Monitoring Devices, Inc., (RMD) is the research business unit of Dynasil Corporation of America. Since 1974 RMD has been a world leader in providing innovative solutions across a broad range of security, medical and industrial applications, including radiation imaging and detection, nuclear instrumentation and non-destructive test equipment. RMD has practices in material science, radiation detection, digital imaging technology, magnetic imaging, laser optics and photonics.

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[1] Annual Report 2011, Hamamatsu Photonics., Jan 2012, http://www.hamamatsu.com/ir/annual_report/common/pdf/anu2011.pdf

[2] "Radiation Detection Materials Markets." 2011. Nanomarkets web site. http://ve.crxc7qw5.vesrv.com/images/uploads/Nano-386_Sample.pdf.

RMD is an acknowledged technical innovator that has completed many research and development contracts. RMD employs 132 scientists, engineers and manufacturing personnel; including 44 PhD level and 12 M.S. level scientists.

RMD is “the science behind the technology” at Dynasil. Our research serves as the incubator for new product innovation, directly supporting the commercialization efforts of Dynasil’s Products and Technologies business segment. We believe what differentiates our organization is this enviable combination of world-class research and manufacturing. This combination enables us to be far more nimble and efficient in advancing products from the research lab to the marketplace. For example research performed on our ground breaking dual-mode scintillation crystals has flowed from the RMD’s Watertown, Mass lab to Dynasil’s Hilger Crystals division, where it is being commercialized. We are also collaborating with Dynasil Products on RMD’s digital dosimeters research, and on Dynasil Products RadCam gamma detection system.

Major U.S. government agencies, including the Department of Homeland Security, the Domestic Nuclear Detection Office, the Department of Energy, the Department of Defense, the National Institutes of Health, NASA and the National Science Foundation support our work in developing specialized technologies to make the world a safer and healthier place. In recognition of our work and our outstanding contributions to the SBIR program, the U.S. Small Business Administration awarded RMD the National Tibbett’s Award in 2002 and again in 2012.

Dynasil/RMD Merger

On July 1, 2008, RMD Research and RMD Instruments merged with Dynasil Corporation of America. Employing 237 people (Including RMD Research), Dynasil is a publicly traded (NSD: DYSL), growth-oriented engineering and manufacturing company developing optical components, thin film coatings, and other products that reinforce and complement RMD’s research. In October 2010, Dynasil was recognized as one of the 500 fastest growing technology companies in North America, ranking 175th on Deloitte LLP’s 2010 Technology Fast 500™ list. Rankings are based on percentage of revenue growth during the period of 2005 to 2009. Dynasil's revenue grew 577 percent during this time.

Dynasil Products (formally RMD Instruments) commercializes the technologies developed at RMD, Inc. Dynasil Products is a vertically integrated company that manufactures, markets and sells to both end users and to OEMs worldwide utilizing its own sales force, as well as partnering with distributors. Dynasil Products is an ISO-9001 company, and operates its production facilities to meet all FDA, EPA and government requirements and consistently passes all FDA and government inspections.

Commercialization Team

Dynasil and RMD’s growth strategy is built on commercializing of our world class research portfolio, organic growth of existing products and acquisitions of new technologies to speed time to market. We have put together a team of people with the necessary experience to bring our products to market. Combined with the development team, they bring the management, financial, technical, sales and marketing skills to ensure that we successfully build market share.

Kanai Shah, President – RMD

Dr. Shah oversees RMD's research and development activities in the areas of materials science (particularly, scintillators and semiconductors) and photodetection. He has been Principal Investigator and Program Manager on numerous programs funded by various government agencies including DOE, DNDO, NIH, NASA, NSF, and DOD to develop materials, sensors and instruments. He is also managing DNDO funded low rate production of two new scintillation materials and his research has led to licensing agreements with multinational corporations. Dr. Shah received his Ph.D. from Delft University of Technology in the Netherlands. He joined RMD in 1985. He became RMD's Vice President of R&D in 2009 and President of RMD in 2011.

Richard Johnson, Chief Financial Officer – Dynasil Corporation

Prior to joining Dynasil in November of 2009, Mr. Johnson served as Chief Financial Officer for Tejas Research and Engineering, an engineering and manufacturing firm in the oil and gas industry. He served as COO at Mondrian-Hall, Inc., Canada's leading supplier of imaging equipment, supplies and service to the technical, display graphics and photo marketplace, from 2006 to 2007. From 1989 until 2006, he held numerous financial positions of increasing responsibility, including Treasurer, VP Finance, and CFO at Charrette Corporation. Mr. Johnson has a B.S. and an M.B.A. in Finance.

Joanne Gladstone, Vice President Operations – RMD

Ms. Gladstone joined RMD Inc. as the Director of Strategic Planning in April 2005. Prior to RMD, she was Chief of Staff of the Chickering Group, a leading brokerage firm specializing in providing health benefits to college students. Ms. Gladstone has an extensive background in strategic planning, market research and technology commercialization. Ms. Gladstone earned her B.A. in Psychology from Brandeis University and her Masters in Management from the Heller School of Social Policy and Management at Brandeis University.

Martin Waters, Director of Commercial Development – RMD

Mr. Waters joined RMD Inc. as the Director of Commercial Development in 2008. Mr. Waters has over 20 years' experience in channel, OEM and sales management with Hewlett-Packard, SGI, Sybase, and Informix. He has developed channel partner relationships that generated over $60 Million on an annual basis. He earned his B.S. in finance and marketing

Scintillator and Detector Commercialization Strategy

In 2010 Dynasil and RMD made the decision to begin commercialization of our scintillation materials and detector research. We are utilizing a three tiered approach to bring our products to market. The first strategy is to work with one of Dynasil's manufacturing divisions to undertake manufacturing. The second approach is to develop a joint partnership with a company who has the technical skills to produce the product as well as the sales and market capacity to capture market share. Finally, we will license certain technology to third parties who are uniquely positioned to capture significant market share while paying us a yearly royalty.

Thin Films Manufacturing

RMD is a pioneer in developing thin and thick film deposition techniques that will be invaluable in manufacturing the proposed MCP-PMTs. We began this work in the late 1970's and received our first patents in 1982. (Method to synthesize and produce thin films by spray pyrolysis: Patent #s 4338362 U.S. – 7/6/1982, 4336285 U.S. – 6/22/1982 and 4327119 U.S. 4/27/1982) RMD is currently transferring our experience in E-Beam Evaporation, Physical Vapor Deposition, Sputtering, and Hot Wall Evaporation to our sister division, EMF (Ithaca, NY) to commercialize our CsI thin film technology. Basing the production of CsI thin films at this facility has the following advantages:

1. Familiarity with core manufacturing technology: Both CsI and metal thin film coatings use similar vacuum-based batch coating techniques. EMF understands and works with this core technology daily – and has the personnel trained in its on-going support.
2. Thin metal films are integral to RMD's technology: EMF routinely deposits these films today and can also engineer tailored metal films with customized reflective and absorbance properties – an advantage for future products.
3. Understanding of "Packing Factor" Manufacturing: Unlike the assembly/test of electronic products where costs scale with production volumes, both metal and CsI thin films are produced in batches. Costs are fixed whether there is one or 1000 substrates placed inside a deposition chamber. This ability to manage the "Packing Factor" is the critical driver for controlling manufacturing margins. This knowledge is at the core of EMF's business today.
4. Masking knowledge: Several product configurations require that substrates be mechanically masked to prevent overspray of materials onto critical components. This capability exists at EMF today.
5. Existing cleanroom infrastructure: EMF has raised-floor rooms that were built to be being used as cleanrooms. This space can be converted into Class 1000 clean room space by adding HEPA filters to already existing air handling systems in the ceiling.
6. Proximity to potential customers: Carestream (Rochester, NY) Teledyne-Dalsa (Waterloo, Ontario, Canada) and GE (Niskayuna, NY) are all within six hours drive of EMF. Such proximity could provide competitive advantage in supply chain costs and inventory turns should we secure them as customers.
7. New production capabilities are saleable to others: Added cleanroom processing and parylene coating capabilities will enhance the services EMF can offer to other customers outside of those using CsI thin films.
8. Stable and dedicated workforce: EMF's location in Ithaca has enabled it to develop and maintain a skilled workforce. Such stability will be essential to maintain the skill set needed for consistent production of CsI thin films.

Scintillator Crystal Manufacturing

To commercialize our bulk crystal scintillators RMD is partnering with our sister division, Hilger Crystals Ltd. Hilger Crystals has a long history of supplying high-quality synthetic crystals for infrared spectroscopy, X-ray and gamma ray detection. Applications for synthetic crystals include homeland security, medical imaging, oil exploration, and chemical analysis.

By combining RMD's research and development expertise with Hilger's highly specialized proficiency in the growth and manufacturing of crystals, we can accelerate the commercialization and distribution of RMD's technology portfolio. Hilger Crystals was acquired on July 20, 2010 specifically to accelerate RMD's ability to commercialize our halide scintillators; CLYC and Strontium Iodine. The acquisition exemplifies our growth strategy to acquire companies with strengths in complementary areas, which enables us to more quickly commercialize our new technology while expanding the scale and scope of our product line and distribution channels.

Licensing – Cerium Bromide to Hellma Materials

Part of RMD's long term commercialization strategy is to license materials to other companies. This enables us to maximize revenue and return on our R&D investments. RMD is commercializing one of our most promising crystal scintillators, Cerium Bromide ($CeBr_3$) by licensing the world-wide rights to Hellma Materials. Hellma will be producing crystals for the medical, homeland security and well logging markets. Our goal is to maximize our ability to bring new products to market as quickly as possible to capture significant market share.