Higher Education Research Council
Idaho Global Entrepreneurial Mission Program
Year End Report

Proposal No.	**IGEM16-02**
Project Title:	**Idaho Microfabrication Laboratory**
Name of Institution:	**Boise State University**
Principle Investigator (s):	**Kurtis Cantley**
Reporting Period:	**July 1, 2015 – June 29, 2018**

1. **Summary of Project Accomplishments**

The overall goal of this IGEM project was to support the Idaho semiconductor and microelectronics industry by enhancing relevant infrastructure, equipment, expertise, and educational programs at Boise State University. Augmenting nanotechnology and microfabrication capabilities in the Idaho Microfabrication Laboratory (IML) was a specific focus. The IML is a recharge center containing the largest university clean room in Idaho (approximately 2500 ft^2) as well as the adjacent 900 ft^2 Additive Manufacturing Laboratory. The facility is equipped to perform deposition, etching, micro- and nano-scale patterning, and physical and electrical characterization.

The capacity and use of the IML grew tremendously during the three-year grant period which was catalyzed by the support provided by IGEM. This progress is evidenced by multiple metrics: 1) Total IML student usage hours quadrupled over the grant period, climbing from 654 in FY 2015 up to 2627 in FY 2018. 2) The number of active student users logging billable hours approximately doubled, from 19 in FY 2013, to 23 in FY 2014-2015, to 39 in FY 2018. 3) Faculty utilization increased from 13 in FY 2013 to 24 in FY 2018. 4) The number of grant proposals submitted requiring IML equipment or resources increased from 11 in FY 2014 to 33 in FY 2018. 5) The number of hours charged to external users increased from effectively zero in FY 2014 to approximately 170 equivalent hours (from six different organizations) in FY 2018. The grant also permitted hiring of new faculty and staff, and supported multiple PhD students. The IML is now positioned as a critical facility for a growing number of internal and external users performing a wide variety of research.

The initial IGEM proposal outlined four strategies aimed at cultivating innovative research and development opportunities centered on the IML. Specific details regarding the outcomes from each strategy are outlined below:

I. Perform infrastructure improvements, capacity-building equipment acquisition, and hire additional staff to increase operational efficiency and support capability of the IML.

The appearance, functionality, and utilization of the IML has completely transformed over the duration of this IGEM grant. Equipment purchased as part of the project has not only significantly increased safety, but also research output through reduction and (in some cases) elimination of scheduling conflicts by different users. One example is the purchase of separate chemical processing stations for acids, bases, and solvents, which allows three or more users to safely perform tasks and experiments simultaneously. In contrast, the IML previously had a single chemical bench, for which safety dictated that only one class of chemical could be used at a time. A number of deposition, etching, and metrology tools were also purchased and are now a critical component of many user processes.

Equipment used for semiconductor processing and microfabrication often cannot be simply purchased and placed on a desk or tabletop. The complex equipment typically requires very specific facility connections, and many factors must be considered in the process of installation. Chief among these are the facility connections to the tool and ensuring that liquid waste or ventilation effluents are compatible with environmental regulations and safety standards. Broad expansion in these infrastructure systems was therefore undertaken as part of the project, including: 1) Additional 100 Ampere (208 Volt 3-phase) power service completed in conjunction with Department of Public Works replacement of the building transformer. 2) An ultra-pure nitrogen distribution system throughout the clean room supplied by a high capacity liquid dewar tank. 3) De-ionized water line extension and replacement. 4) Doubled thermal capacity of the chilled water system (in conjunction with a Facilities, Operations, and Maintenance project). 5) Improved vacuum system. 6) Numerous improvements to the ventilation and exhaust system to create more balanced flow and positive pressure in the clean room. While the impact of these upgrades is difficult to quantify, they are critical for continued growth and expansion of IML capabilities well into the future.

Finally, the grant funded the hiring and two years of salary for a technical support engineer (Travis Gabel), who was responsible for troubleshooting equipment issues, performing safety inspections and maintenance, and training users. Having experienced staff who are able to constantly monitor the equipment, assist users, and perform process qualification is crucial to sustained success of the facility in terms of research impact and revenue.

II. Expand expertise in three strategic research areas of strength through a tactical new faculty hire and subsequent support.

The initial proposal called for the hiring of a new Electrical and Computer Engineering (ECE) tenure-track faculty with preferred emphasis in one of three emerging research areas. These areas were identified as flexible and printed electronics, thin-film and 2-dimensional (2D) materials, and neuromorphic computing. The faculty member hired with IGEM support (Dr. Harish Subbaraman) has already received significant external funding and has been performing impactful flexible and printed electronics research in the IML. The creation of this faculty position also helped facilitate numerous local, regional, and national research collaborations.

III. Increase industrial partnerships and research collaborations with Boise State by providing straightforward access and technical support to the IML.

Over the duration of the project, use of the IML by external organizations has increased from effectively zero hours in FY 2014 to over 170 equivalent hours in both FY 2017 and 2018. With some equipment rates exceeding $100/hr and additional surcharges for precious metal use, this usage corresponds to approximately $19,000 in revenue per year, coming from five different local companies. It amounts to 37% of the overall revenue of $51,000 generated by user fees. IML leadership, the ECE department, and the College of Engineering continues to work toward further expansion of mutually beneficial partnerships and agreements.

IV. Create additional education and training opportunities in the areas of nanotechnology and microelectronics for industrial partners and students.

The educational aspects of this IGEM project provided students considerably more opportunity to utilize the IML and become trained on equipment and processes pertinent to local industry. As previously described (and also detailed in section 4), the number of student users and student use hours increased dramatically during the project period. At the same time, the number of students enrolling in courses utilizing the IML also increased. In fall 2017, the ECE 440L/540L (Introduction to Integrated Circuit Processing) course had 12 students enrolled. In spring 2018, a new ECE 497/597 (Memristor Fabrication) class taught by Prof. Kris Campbell had 18 students enrolled. In this class, students utilized the IML extensively to implement a full resistive memory device fabrication process flow. The MSE 280 (Intro to Materials Lab Practice) course taught by Prof. David Estrada in spring 2018 had 15 students involved in projects that use the IML in some capacity for materials development. In addition, ECE 621 (Electrical Characterization of Semiconductor Materials and Devices) was added to the curriculum, and was last offered as ECE 697 in Fall 2016 with enrollment of 9 student. The course is complementary to the IML and has a lab component in which devices fabricated in the IML are tested and characterized. Additional offerings of ECE 441L/541L (Advanced Silicon Processing) and ECE 442L/542L (Photolithography) are planned in the upcoming two years, both of which will use the IML extensively. Many employers consider these types of hands-on learning activities to be very positive experiences.

2. **Summary of Budget Expenditures**

Spending under this grant typically fell into four main categories: 1) Salaries and fringe benefits, 2) Major equipment purchase, 3) Infrastructure and operational or safety improvements, and 4) Other, which generally includes materials, supplies, and consumables. The project paid for portions of the clean room director's salary as well as the entirety of the new technical support engineer salary over the duration of the project. In years 2 and 3, the grant also paid for the salary of the new ECE tenure-track faculty member, and part or all of multiple graduate student stipends and fees (see Section 4 for details). Brief descriptions of the major expenditures exceeding $10,000 for categories 2, 3, and 4 are listed below by year. Dollar values are approximate.

Year 1:

- $48,000 for purchase of the Fuji Dimatix DMP-2831 Materials Printer
- $52,000 for purchase of the Bruker Dektak XT-A stylus profilometer
- $192,000 for the three new wet chemical processing stations from JST Manufacturing, Inc.
- $16,000 for the Zeiss Axio.A1 materials inspection microscope
- Approximately $70,000 in total for supplies, and facility and equipment upgrades and installation

Year 2:

- $45,000 for purchase and installation of the new asher/reactive ion etching system (PVA TePLA Ion 40)
- $25,000 dedicated to lab chilled water supply upgrade (joint project with Boise State Facilities Operations and Maintenance)
- Approximately $52,000 in total for supplies, and facility and equipment upgrades and installation
- $10,000 matching funds provided to Profs. David Estrada and Harish Subbaraman for a successfully funded DOE proposal for electronic ink development and metrology equipment (complementary to IML areas of focus)

Year 3:

- $25,000 for endpoint detection and Argon gas upgrades to the Oxford PlasmaLab 180 etcher
- $30,000 for purchase of a second AJA International Orion sputtering system from from QTI, Inc., as well as additional $21,000 in upgrades to this system
- $15,000 toward a Space Foundry, Inc. plasma jet printing system
- $20,000 for a new four point resistivity measurement system manufactured by Lucas Signatone Corporation
- Approximately $104,000 in total for supplies, and facility and equipment upgrades and installation

3. Demonstration of Economic Development/Impact

The sections below provide data regarding technology licenses, start-up businesses, industrial use hours for the IML and other forms of private sector engagement, and a detailed list of external funding for projects that require the IML facility.

a) Patents, Copyrights, Plant Variety Protection Certificates received or pending.

FY17:

197 Watkins, Elquist, Warren, Riggs, Estrada, Fujimoto - STARShiP: STrain sensing using AeRosol jet Printing of flexible capacitive strain gauges
194 Campbell - Optically activated switch, photodiode and transistor
193 Browning, Cornell - A Plasma Scalpel for Selective Removal of Microbes and Microbial Biofilms
190 Campbell - BEOL Processing of Memristor Devices
187 Paul Lindquist- Ferro Magnetic Shape Memory Alloy Microcavity Fluid Sensor
185 Zhang, Varghese - Printing Thermoelectric materials and devices using nanostructured materials
174 Mullner - Self-Resetting Power Breaker

FY18:

206 Amanda Strong, Elton Graugnard, and Kyusang Lee, Transition metal guanidinates and heteroleptic compounds for chemical vapor deposition and atomic layer deposition
215 Twinkle Pandhi and David Estrada, Flex biosense sensor

b) Technology licenses signed, start-up businesses created, and Industry Involvement

One new start-up was created as a direct result of the support provided by IGEM. Specifically, IGEM established additional capabilities in the area of additive manufacturing and printing in the IML and resulted in the hiring of Dr. Harish Subbaraman. The company, **InFlex Labs, LLC** was co-founded in May 2018 by Dr. Subbaraman and Dr. David Estrada.

Memristor (resistive memory) technology and processing techniques developed by Prof. Kris Campbell in the ECE department continues to be licensed by Knowm, Inc. and M. Alexander Nugent Consulting (MANC) of Santa Fe, NM. Their projects have been ongoing, resulting in significant use of and revenue for the IML, and accounting for approximately 25% of all licensing revenue at Boise State in calendar years CY 2016 and CY 2017.

c) Private sector engagement

On March 10, 2017 the Boise State College of Engineering and Department of Electrical and Computer Engineering co-sponsored an industrial roundtable forum. Numerous local companies were invited to attend and learn about the facilities at Boise State, with a heavy focus on the capabilities of the IML. The networking event fostered beneficial collaborations between faculty and local companies. Figure 1 shows photographs taken at the event, which was successful in highlighting the capabilities of the IML and the ECE department. A list of external companies or organizations having representatives in attendance is provided in Table 1.

Figure 1. Photographs of attendance at the poster session and overview talks at the ECE Industry Forum in 2017.

Table 1. Organizations in Attendance at the ECE Industry Forum

Company	**Company**
AlloSys Corp.	Fiberguide
Campbell Company	Idaho Small Business Development Center
CTS, Inc.	PakSense (Emerson Technologies)
JST Manufacturing	PKG (UIS)
Natural Intelligence Semiconductor	Micron Technology
C4 Technology	Plexus
Centimark	Northwest Nazarene University
Cradlepoint	

In addition to the Industry Forum, the IML is often featured in facility tours for many additional events. Examples include the HPICS conference (sponsored by HP), the Materials Science Roadmap and Capabilities Meeting (sponsored by CAES and Idaho National Lab).

d) Jobs created

The number of jobs created as a direct result of IGEM funding and of any research performed in the IML is not easily quantifiable. New jobs would generally be an indirect result of a sequence of events in which research generated additional profit for a company, thereby allowing them to fund new positions. However, it should be stated that jobs in companies performing any type of advanced manufacturing do not exclusively involve high-level engineering, but necessitate the hiring of support technicians and people with skills not provided by an advanced degree.

e) External Funding

As of FY 2018, the Office of Sponsored Projects (OSP) at Boise State is tracking the number of submitted grants that budgeted for IML use. Most of the information presented in this section was gathered by reaching out individually to faculty that serve as principal investigators (PIs) on grants utilizing the IML. Figure 2 shows the total dollar amounts requested and the amounts awarded by year (since FY 2014) for all grant proposals submitted in the College of Engineering that require some amount of IML use. **A**

decreasing trend entering FY 2016 was completely reversed by changes made possible with IGEM support.

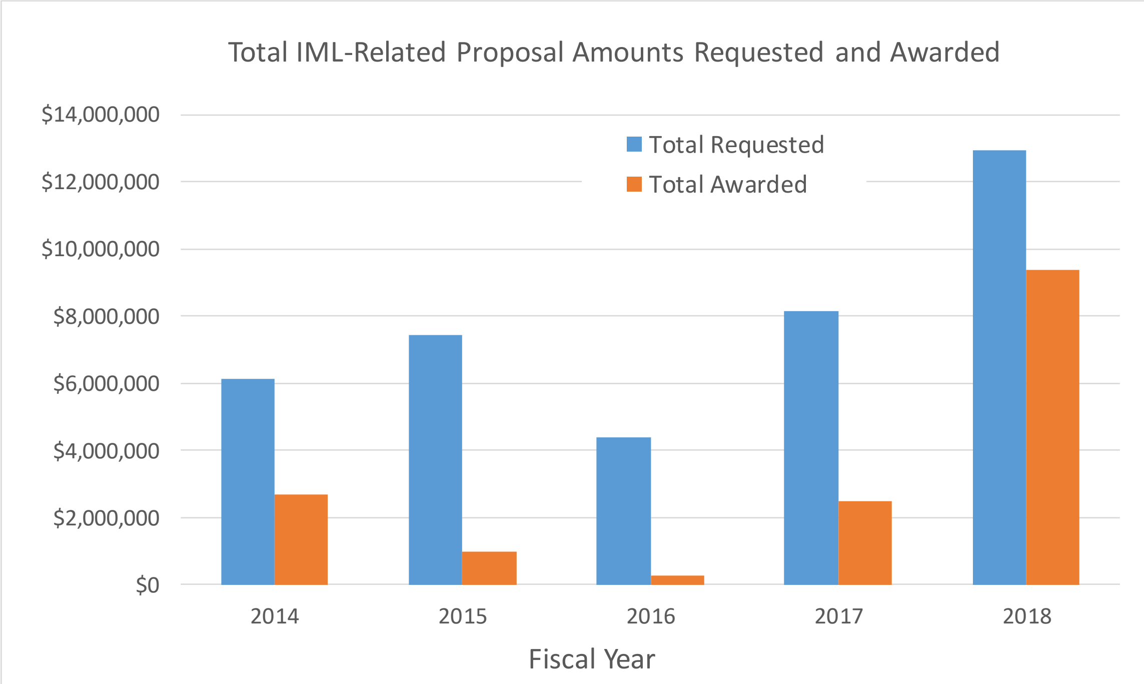

Figure 2. Total dollar amounts requested and awarded for IML-related proposals from FY 2014 through FY 2018.

In any given year, the amounts budgeted for IML use can vary significantly. An example is FY 2016, in which a $228,000 grant was received by Prof. Kris Campbell, of which $150,000 was expected to be spent in the IML. This type of grant is an outlier compared to most, since IML usage is typically a smaller fraction of the total budget. Since this data is generally highly variable, **the best evidence of IGEM impact can be seen in the actual number of faculty whose research groups utilize the IML, the number of proposals submitted that utilize the IML, and the number of unique PI's on those submitted proposals (Figure 3)**. The years between FY 2015 and FY 2017 each saw an increase in the number of IML-related proposals submitted of roughly 20%. That number doubled between FY 2017 and FY 2018. The number of unique PI's on those proposals doubled between FY 2016 and FY 2017, and then doubled again in FY 2018. There are currently about 24 faculty whose students use the facility regularly. The number of active users is larger than the unique PI's in any given year since not all faculty users are necessarily submitting IML-related proposals every year.

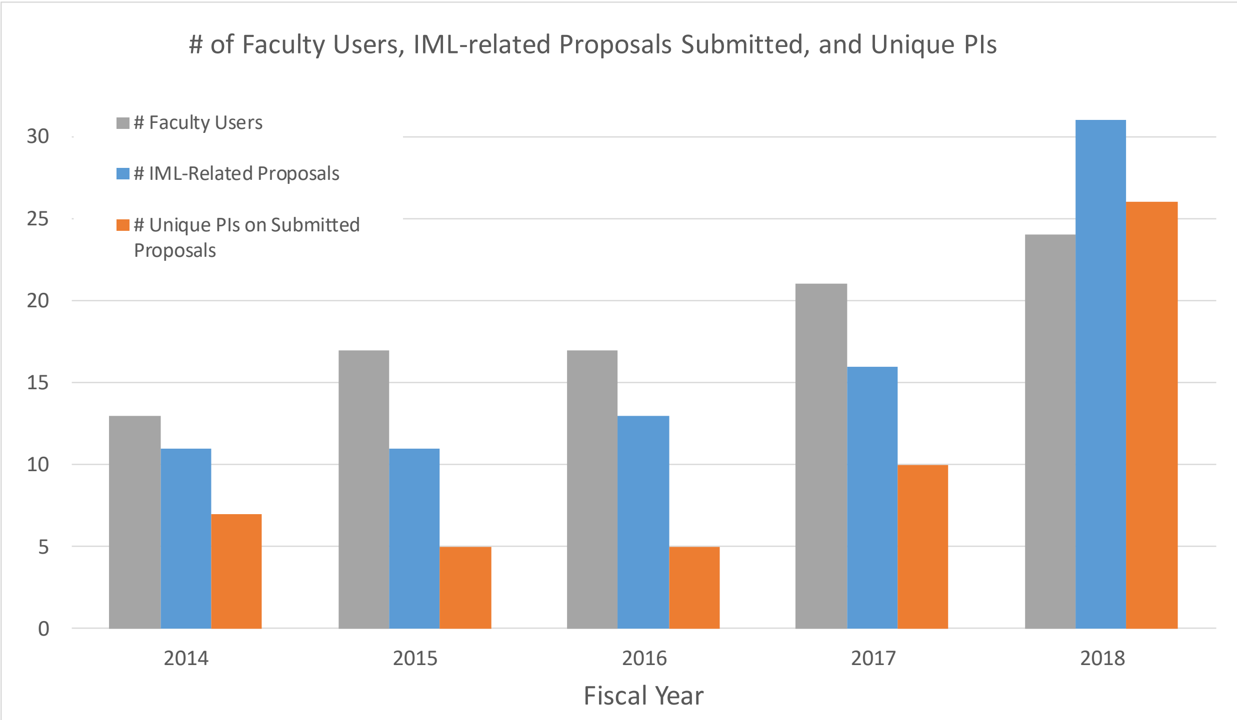

Figure 3. The number of faculty users, proposals submitted requiring the IML, and overall number of unique PIs on those proposals has continued to grow. This clearly demonstrates the research impact of the IML.

The following tables list every IML-related proposal submitted by College of Engineering faculty since FY 2014. Shaded rows indicate that the proposal was funded by the sponsoring agency. It is also important to note that amounts budgeted for use in the IML often differ significantly from the actual amount spent.

FY 2014

PI Name	Co-PI(s) and Affiliation	Project Title	Sponsoring Agency	Total Requested Funds	Total IML Budget	Duration (years)
Cantley, Kurtis D.		Spike Timing-Dependent Learning Circuits for Temporal Pattern Recognition and Classification	AFOSR	$359,429	$28,160	3
Cantley, Kurtis D.		Neuro-Inspired Pattern Recognition and Learning Circuits with Advanced Synaptic Plasticity and Connectivity	DARPA	$483,976	$37,600	2
Campbell, Kristy A.		Memristor Design and Test	MANC/AFRL	$27,179	$15,000	1
Campbell, Kristy A.		Cleanroom Infrastructure	Idaho SBOE	$73,000	$73,000	1
Campbell, Kristy A.		Memristor Design and Test Part 2	MANC/AFRL	$66,420	$50,000	1
Estrada, David		Tunable Thermal Transport in Atomic Layer Materials and Heterostructures	NSF	$560,000	$48,000	3
Xiong, Hui (Claire)		CAREER: Defect-driven Metal Oxides for Enhanced Energy Storage Systems	NSF	$552,213	$2,500	3

Graugnard, Elton	David Estrada, Lan Li, Claire Xiong, Yanliang Zhang	Toward Low power 3D electronics, thermoelectric energy conversion, and electrochemical energy storage	NSF EFRI	$2,000,000	$28,800	4
Graugnard, Elton	David Estrada, William B. Knowlton, Wan Kuang	MRI: Development of an optoelectronic scanning probe	NSF MRI	$400,000	$2,880	3
Mitkova, Maria		Basic Radiation Effects mechanisms in Chalcogenide Based Nanoionic Structures	DTRA	$601,060	$12,500	4
Zhang, Yanliang	Darryl Butt	Nanostructured bulk thermoelectric generator for efficient power harvesting for self-powered sensor networks	DOE	$980,000	$3,000	3

FY 2015

PI Name	Co-PI(s) and Affiliation	Project Title	Sponsoring Agency	Total Requested Funds	Total IML Budget	Duration (years)
Browning, Jim	Tayo Akinwande, MIT	Phase-Controlled Magnetron Development	AFOSR	$448,572	$2,800	3
Cantley, Kurtis D.	Sabrina Jedlicka (Lehigh University)	Neocortical Augmentation: Interfacing Flexible Neuromorphic Electronics with Biological Networks	NSF BME	$330,349	$14,400	3
Cantley, Kurtis D.		CAREER: Electronic Neural Circuits with Efficient Rate and Timing-Based Synaptic Learning	NSF CISE	$574,846	$43,200	5
Cantley, Kurtis D.		Neural Network Signal Detection for Chemical and Biological Sensor Transistor Arrays	NSF CCSS	$288,801	$18,000	3
Campbell, Kristy A.		Memristor Characterization: Single Device and In-Circuit Testing	MANC/AFRL	$80,228	$10,000	1
Campbell, Kristy A.		Phase II STTR with BIT Request for Extension to Include Device Modeling	US DoD	$40,000	$25,000	1
Campbell, Kristy A.		MANC Memristor Fabrication Project	MANC	$10,589	$8,000	1
Estrada, David	Rashid Bashir (U. Illinois)	2D Materials Beyond Graphene for Solid-State Nanopore Biosensors	NSF	$300,000	$18,600	3
Estrada, David	Ilia Solov'yov (U. Southern Denmark)	Exploring the Interaction of Stem Cells and Graphene for Innovations in Tissue Engineering	HFSP	$900,000	$45,000	3
Simmonds, Paul J.	David Estrada, Huaxiang Fu (U. Arkansas), Melinda Hamilton (U of I), Gregory J Salamo (U. Arkansas)	RII Track-2 FEC: Novel Tensile Strained Nanomaterials for Thermo-Photovoltaics	NSF EPSCoR	$3,958,218	$47,392	4
Simmonds, Paul J.		CAREER: Novel nanomaterials for scalable entangled photon emitters	NSF CAREER	$507,000	$13,000	5

FY 2016

PI Name	Co-PI(s) and Affiliation	Project Title	Sponsoring Agency	Total Requested Funds	Total IML Budget	Duration (years)
Campbell, Kristy A.		Reimbursement for Cost of Fabricating Wafers	Knowm Inc	$2,564	$2,500	1
Campbell, Kristy A.		MANC Memristor Fabrication Project	MANC	$2,845	$2,800	1

Campbell, Kristy A.	Anakodec, LLC	Optimal Storage of Multimedia on Memristors using Analog Coding	NSF	$15,000	$8,000	3
Campbell, Kristy A.		SOW for Wafer Fabrication for MANC	Knowm Inc	$10,581	$10,581	1
Campbell, Kristy A.		Boise State University Device Design and IML BEOL Optimization	MANC/DoD	$227,999	$150,000	1
Campbell, Kristy A.		SBIR Innovative Research Phase I	NSF	$20,000	$15,000	1
Estrada, David	American Semiconductor, Kirk Smith, Jessica Koehne (NASA Ames)	Integration of 2D Materails and Flexible Silicon For Wearable Human Monitoring Systems	NextFlex	$300,000	$30,000	3
Estrada, David		Integrating Atomic Layer Materials with Stem Cells for Innovations in Tissue Engineering	Beckman Foundation	$750,000	$30,000	3
Estrada, David	Maria Mitkova, Yanliang Zhang, Hao Chen	A Flexible Hybrid Approach to Wireless Sensor Networks for Nuclear Applications	DOE NEUP	$1,000,000	$45,000	3
Graugnard, Elton	David Estrada, Lan Li, Paul Simmonds	Modeling, Synthesis, and Characterization of Atomic-Layered Transition Metal Dichalcogenides	DOE EPSCoR Lab Partnerships	$598,000	$9,500	3
Saxena, Vishal	Maria Mitkova	E2CDA: Type II: Heterogeneous Memristive Photonic Neuromorphic Computing Architecture	NSF	$596,749	$9,000	3
Mehrpouyan, Hani		Molecular Communication: Unleashing the Internet of Bio-Nano Things	DARPA	$490,000	$15,000	3
Mehrpouyan, Hani		Bio-inspired Molecular Communications for Connecting Swarm of Robots	AFOSR	$360,000	$15,000	3

FY 2017

PI Name	Co-PI(s) and Affiliation	Project Title	Sponsoring Agency	Total Requested Funds	Total IML Budget	Duration (years)
Cantley, Kurtis D.		Detection of Neuronal Firing Events Using Nanowire Thin-Film Transistors and Circuits	ARO	$360,000	$28,800	3
Cantley, Kurtis D.		Fully Configurable Electronic Neural Networks using Advanced Memory	SRC	$775,101	$19,500	5
Campbell, Kristy A.		BEOL memristor fabrication for Nazarbayev University, Astana, Prof. Alex James	Govt. Astana	$3,066	$3,000	1
Campbell, Kristy A.		Memristor BEOL through Knowm Inc for Dietmar Fey, University of Erlangen	University of Erlangen, Germany	$10,000	$8,000	1
Estrada, David	Emily Heckman (AFRL)	2D materials for Flexible Hybrid Electronics	AFRL	$52,000	$2,500	1
Estrada, David	Maria Mitkova, Yanliang Zhang, Jessica Koehne (NASA Ames), Harish Subbaraman, Kris Waynant (U. Idaho)	Space Grade Flexible Hybrid Electronics	NASA EPSCOR	$750,000	$30,000	3
Xiong, Hui (Claire)	Yanliang Zhang, Min Long, Herbert Hess (U. Idaho)	Flexible and High-Power-Density Integrated Thermoelectric Generator and Battery SystemThrough Additive Manufacturing of Nanomaterials	NASA EPSCOR	$750,000	$3,000	3

Simmonds, Paul J.		Tensile-strained nanostructures for high efficiency thermoelectric materials	DOE Early Career	$751,000	$13,000	5
Subbaraman, Harish	Yanliang Zhang, Ray Chen (UT Austin), Xiangfend Duan (UCLA)	SNM: Scalable manufacturing of high performance flexible integrated systems incorporating ink-jet printed nanogap-channel transistors	NSF: SNM-IS	$1,168,362	$12,804	4
Subbaraman, Harish		Silicon Nanomembrane Enabled Photonic Integrated CIcuits for Light-Weight and Conformal True-Time-Delay Subsystem Development for Space Applications	NASA Early Career	$492,906	$15,000	3
Graugnard, Elton	David Estrada	Synthesis and Characterization of Atomic-Layered Transition Metal Dichalcogenides	Micron Foundation	$62,835	$780	2
Mitkova, Maria	Harish Subaraman	Integrated Silicon/Chalcogenide Glass Hybrid PlasmonicSeneor for Monitoring of temperature in Nuclear Facilities	DOE	$890,000	$9,000	3
Browning, Jim	Julia Oxford, Ken Cornell	Dynamically Controlled Plasma Scalpel for Biofilm Wound Debridement	NIH	$400,338	$1,000	3
Subbaraman, Harish		MRI: Development of a High Speed Roll-to-Roll printer for Flexible Electronics Advancement	NSF	$965,775	$0	1
Estrada, David	Harish Subaraman	Development of Nuclear Grade Nanoparticle Ink Syntheses Capabilities for Advanced Manufacturing of Nuclear Sensors	DOE	$295,392	$0	1
Ubic, Rick	Noah Salzman	REU Site: Materials for Society	NSF	$425,984	$1,050	3

FY 2018

PI Name	Co-PI(s) and Affiliation	Project Title	Sponsoring Agency	Total Requested Funds	Total IML Budget	Duration (years)
Browning, Jim	MIT	Empty State Electronics	AFOSR	$720,000	$18,000	3
Browning, Jim	Cornell (Boise State)	Cold Plasma Source for Treatment of Food and Food Processing Equipment to Enhance Food Safety	USDA	$150,000	$1,200	1.5
Browning, Jim	Cornell (Boise State)	Plasma Debridement of Chronic Wounds	NIH	$440,000	$2,000	3
Ubic, Rick		REU Site: Materials for Society	NSF	$425,983	$0	3
Subbaraman, Harish	Estrada (Boise State)	A Flexible Wireless Sensor Network Enabled Miniaturized Air Scrubber System for Protecting Time Critical Inventory	IGEM, Idaho Department of Commerce	$413,681	$0	1
Estrada, Dave	Subbaraman, Jaques, Jankowski (Boise State)	Advanced Manufacturing for In-Pile Nuclear Sensors	DOE	$231,171	$10,000	1
Jaques, Brian	Li, Callahan, Kandadai, Subbaraman, Estrada (Boise State)	In-Pile Instrumentation Initiative: Work Package 8: Mechanical Properties	DOE	$140,000	$4,000	1
Li, Lan	Jaques, Cantley, Kandadai, Estrada	In-Pile Instrumentation Initiative: Work Package 2: Field Properties	DOE	$132,463	$5,000	1
Estrada, Dave		In-Pile Thermal Properties Measurement and Thermography - MSMSE	DOE	$98,247	$5,000	1

Estrada, Dave		Additive Manufacturing of Functional Materials and Sensor Devices for Nuclear Energy Applications	DOE	$250,000	$0	1
Estrada, Dave	Subbaraman (Boise State)	Development of Nuclear Grade Nanoparticle Ink Synthesis Capabilities for Advanced Manufacturing of Nuclear Sensors	DOE	$340,784	$0	1
Estrada, Dave	Subbaraman, Mitkova (Boise State), Waynant (U. Idaho)	Space Grade Flexible Hybrid Electronics	NASA	$1.125M	$10,000	3
Mitkova, Maria	Subbaraman (Boise State)	Integrated silicon/chalcogenide glass hybrid plasmonic sensor for monitoring of temperature in nuclear facilities NEET – 2.1	DOE	$890,000	$10,000	3
Mitkova, Maria	Tenne (Boise State)	In pile direct structural characterization	DOE	$225,000	$3,000	3
Mitkova, Maria	van Rooyen (Idaho National Lab)	Embedded thermocouples for in pile temperature measurement	DOE	$820,000	$6,000	3
Rafla, Nader	Mullner	MSM Micropump	IGEM, Idaho Department of Commerce	$343,330	$500	2
Mullner, Peter		NSF/DMR-BSF: Twin boundary structure and mobility in shape memory alloys	NSF	$499,065	$500	3
Smith, Aaron	Mullner	STTR Phase I: MSM uPump: Precision dosing for laboratory research	NSF (Shaw Mountain Technology)	$67,500	$500	2
Jaques, Brian	Vandegrift (Boise State)	Oxidation of zirconium alloys	DOE-NNSA	$423,173	$3,000	3
Jaques, Brian	Pedersen (Boise State)	Modeling and Design of Borated Aluminum Casks for Used Fuel Storage	IGEM, Idaho Department of Commerce	$128,514	$1,500	2
Jaques, Brian		Novel Temperature Sensor for Nuclear Applications	DOE-SBIR Phase I	$44,581	$3,000	0.7
Graugnard, Elton		Scalable Manufacturing of Two-dimensional Atomic Layer Materials for Energy-efficient Electronic Devices via Selective-area Atomic Layer Deposition	NSF	$500,000	$16,000	5
Graugnard, Elton		Synthesis and Characterization of Gallium Phosphide by Atomic Layer Deposition	Undisclosed	$178,000	$100	1
Hurley, Mike	Graugnard	Electro-Deposition of DNA Masks for Nanolithography	NSF	$309,000	$13,000	3
Hughes, Will	Andersen, Graugnard, Hayden, Kuang	SemiSynBio: Nucleic Acid Memory	NSF/SRC	$1.5 M	$15,000	3
Graugnard, Elton	Estrada (Boise State)	Synthesis and Characterization of Atomic-Layered Transition Metal Dichalcogenides	Micron Foundation	$25,000	$1,250	1
Hurley, Mike		Resolving and simulating microgalvanic couples that drive materials degradation	NSF	$500,000	$12,000	3
Hurley, Mike		Tailoring corrosion properties of additively manufactured austenitic stainless steel	ONR	$460,000	$7,000	3

Cantley, Kurtis		CAREER: Spiking Neural Circuits and Networks with Temporally Dynamic Learning	NSF	$548,882	$16,000	5
Cantley, Kurtis	Johnson, Morrison, Subbaraman (Boise State)	NCS-FO: An Injectable Microsystem for Adaptive Closed-Loop Neuromodulation	NSF	$901,648	$34,100	4
Campbell, Kris		CIGS Nanoparticle Devices: Phototransistors, Memristors, Tunnel Diodes	DOE	$30,000	$11,000	1
Campbell, Kris		NSF RoL: FELS RAISE Using memristance IV curves	NSF	$88,000	$22,000	1

f) Any other pertinent information

Another metric that validates impact of any research facility is affiliated publications and presentations. Unfortunately, data on publications that contained any data obtained in the IML was not fully tracked prior to the current fiscal year. A partial list of citations is provided in Table 2.

Table 2. Partial listing of IML-associated publications and presentations delivered over the grant duration.

Title	Authors	Journal or Conference
Silver photodiffusion into Ge-rich amorphous germanium sulfide—neutron reflectivity study	Y Sakaguchi, H Asaoka, M Mitkova	Journal of Applied Physics 122 (23), 235105, 2017.
Proton Beam Effects on Ge–Se/Ag Thin Films	T Nichol, G Nagy, R Huszank, D Tenne, MN Kozicki, HJ Barnaby, I Rajta, M. Mitkova	physica status solidi b. December 2017. |https://doi.org/10.1002/pssb.201700453]
A Comparative Study on TID Influenced Lateral Diffusion of Group 11 Metals Into Ge x S 1− x and Ge x Se 1− x Systems: A Flexible Radiation Sensor Development Perspectives	A Mahmud, Y Gonzalez-Velo, HJ Barnaby, MN Kozicki, M Mitkova, KE Holbert, M Goryll, TL Alford, JL Taggart, W Chen	IEEE transactions on Nuclear Science v. 64, No. 8 2292-2299, 2017.
Resistance state locking in CBRAM cells due to displacement damage effects	JL Taggart, R Fang, Y Gonzalez-Velo, HJ Barnaby, MN Kozicki, JL Pacheco, ES Bielejec, ML McLain, N Chamele, A Mahmud, M Mitkova	IEEE transactions on Nuclear Science v. 64, No. 8, 2300-2306, 2017.
X-ray irradiation effects on CBRAM devices and Materials studies related to them	Kasandra E Wolf, Mahesh Ailavajhala, Rizwan Latif, Maria Mitkova	Workshop on Microelectronics and Electron Devices (WMED), Boise ID April 21 2017.
Kinetics of Silver Photodiffusion Into Amorphous Ge20S80 Films: Case of Pre-Reaction	Yoshifumi Sakaguchi, Takayasu Hanashima, Hiroyuki Aoki, Hidehito Asaoka, Al-Amin Ahmed Simon, Maria Mitkova	physica status solidi a, March 2018. |https://doi.org/10.1002/pssa.201800049
Photoinduced Mass Transport in Ge-Se Amorphous Films	M Reinfelde, M Mitkova, T Nichol, ZG Ivanova, J Teteris	Chalcogenide Letters, v. 15, No. 1, 35-43, 2018.
Formation of Naonoporous Structure in Chalcognide Glasses for Improvement of Performacne fo CBRAM devices	Maria Mitkova, Mohammad Rizwan Latif	Advanced materials World Congress Singapore, February 4-9 2018.
Parallel Plate Atmospheric Pressure Plasma Source for Destroying Bacteria and Biofilms	Kate Benfield, Tiffany Berntsen, Daniel Moyer, Spencer Goering, Mariah Provost, Zeke Kennedy, Ken Cornell, Julia Oxford, and Jim Browning	IEEE Conference on Plasma Science (ICOPS) 2018.
Mechanical Properties of Graphene Foam and Graphene Foam – Tissue Composites	K.M. Yocham, C. Scott, K. Fujimoto, R. Brown, E. Tanasse*, J.T. Oxford, T.J. Lujan, D. Estrada	Advanced Engineering Materials
High-efficiency and flexible nanostructured thermoelectric materials by low-cost printing of solution-processed nanoplate crystals	T. Varghese, C. Hollar, N. Kempf, C. Han, D. Estrada, R. Mehta, Y. Zhang	Scientific Reports, no. 33135, 2016.

Graphene as a 3-Dimensional Platform for Myotube Growth	E. Krueger, A.N. Chang, D. Brown, J. Eixenberg, R. Brown, S. Rastegar, K.M. Yocham K. Cantley, D. Estrada	ACS Biomaterials Science and Engineering, vol. 2, no. 1234, 2016.
Emerging 2D Nanomaterials for Additive Manufacturing of Space-Grade Flexible Electronics	T. Pandhi, E. Kreit, R. Aga, K. Fujimoto, S. Mohammad, S. Khademi, A.N. Chang, F. Xiong, J. Koehne, E.M. Heckman, D. Estrada	69th International Aeronautics Congress (IAC), Bremen, Germany; Oct. 2018.
Ultrafast Additive Manufacturing of Flexible Thermoelectric Films by Aerosol Jet Printing and Photonic Curing	T. Varghese, R. J. Mehta, D. Estrada, Y. Zhang	37th International Conference on Thermoelectrics (ICT), Normandy, France; Jul. 2018.
Fully inkjet printed graphene-based biosensor for flexible and wearable electronics	T. Pandhi, D. Estrada, J. Koehne	28th World Congress on Biosensors, Miami, FL; Jun. 2018.
Inkjet Printing of Graphene for Wearable and Flexible Electrochemical Sensors	T. Pandhi, D. Estrada, J. Koehne	233rd Electrochemical Society Meeting, Seattle, WA; May 2018.
High-Performance Flexible Thermoelectric Thin Films from Solution Processed Colloidal Nanoplates	C. Hollar, T. Varghese, M. Kongara, Z. Lin, X. Duan, D. Estrada, and Y. Zhang	NASA In-Space Manufacturing and Printed Electronics Workshop, Huntsville, AL; Apr. 2018.
Additive Manufacturing of In – Pile Nuclear Sensors	K. Fujimoto, T. Unruh, J. Watkins, H. Subbaraman, and D. Estrada	NASA In-Space Manufacturing and Printed Electronics Workshop, Huntsville, AL; Apr. 2018.
Emerging 1-D and 2-D Materials for Printed and Flexible Electronics	T. Pandhi, E. B. Kreit, R.S. Aga, K. Fujimoto, M. Sharbati, S. Khademi, A.N. Chang, H. Subbaraman, F. Xiong, J. Koehne, E.M. Heckman, and D. Estrada	NASA In-Space Manufacturing and Printed Electronics Workshop, Huntsville, AL; Apr. 2018.
Inkjet Printing of Dense Interconnect Arrays for Flexible Silicon Circuit Integration on Flexible Substrates	J. Cox*, A. Chandnani, D. Wilson, D. Estrada, H. Subbaraman	Flex Conference, Monterrey, CA; Feb. 2018.
Anisotropic Conductive Adhesives for Flexible Hybrid Electronics	A. Rodriguez*, H. Subbaraman, D. Wilson, D. Estrada	Flex Conference, Monterrey, CA; Feb. 2018.
Three-Dimensional Graphene Foam for Musculoskeletal Tissue	K. Yocham, C. Scott, K. Fujimoto, E. Tanasse*, J. Oxford, T. Lujan, D. Estrada	Biomedical Engineering Society Annual Meeting, Phoenix, AZ; Oct. 2017.
Applications of Atomically Thin Materials from Biomolecules to Engineered Tissue	K. Yocham, E. Krueger, J. Shim, C. Scott, R. Brown, K. Fujimoto, E. Tanasse*, M. Hondros, R. Bashir, T. Lujan, J.T. Oxford, D. Estrada	European Advanced Materials Congress, Stockholm, SE; Aug. 2017.
Signal-to-Noise Ratio Enhancement Using Graphene-Based Passive Microelectrode Arrays	S. Rastegar, J. Stadlbauer*, K. Fujimoto, K. McLaughlin*, D. Estrada, K. Cantley	IEEE International Midwest Symposium on Circuits and Systems, Boston, Ma; Aug. 2017.
High-Performance and Low-Cost Printed Flexible Thermoelectric Devices	T. Varghese, C. Han, J. Richardson, N. Kempf, C. Hollar, R. Danaei, R. Panat, R. J. Mehta, Z. Ren, D. Estrada, Y. Zhang	36th International Conference on Thermoelectrics (ICT), Pasedena, Ca; Jul. 2017.
Additive Manufacturing of In-Pile Nuclear Sensors	K. Fujimoto, K. Davis, T. Unruh, D. Estrada	6th International School for Materials for Energy and Sustainability, (Pasadena, Ca; Jul. 2017
Emerging Materials for Aerosol Jet Printing of Flexible Electronics	T. Pandhi, E. Kreit, R. Aga, K. Fujimoto, S. Mohammad, S. Khademi, F. Xiong, J. Koehne, E.M. Heckman, D. Estrada	International Society for Optics and Photonics (SPIE) International Workshop on Thin-films for Electronics, Electro-Optics, Energy and Sensors (TFE3S), Dayton, OH; Jun 2017.
Enhanced Signal-to-Noise Ratio Using Nanomaterial-Based Passive Neural Electrodes	S. Rastegar, J. Stadlbauer*, K. McLaughlin*, K. Fujimoto, D. Estrada, K. Cantley	Materials Research Society Electronic Materials Conference, South Bend, IN; Jun 2017.
Electrical Transport and Power Dissipation in Aerosol-Jet-Printed Graphene Interconnects	T. Pandhi, E. Kreit, R. Aga, K. Fujimoto, S. Mohammad, S. Khademi, F. Xiong, J. Koehne, E.M. Heckman, D. Estrada	Materials Research Society Electronic Materials Conference, South Bend, IN; Jun 2017.
Aerosol-Jet Printing of Graphene and MoS2 Based Devices for Flexible Electronics	T. Pandhi, E. Kreit, R. Aga, K. Fujimoto, S. Mohammad, S. Khademi, F. Xiong, J. Koehne, E.M. Heckman, D. Estrada	FLEX Conference, Monterrey, CA; Jun 2017.
Inkjet Printed Carbon Nanotube Thin Film Transistors	R. Torsi*, A. Chandnani, B. Joshi, D. Estrada, and H. Subbaraman	IEEE Workshop on Microelectronics and Electron Devices (WMED), Boise, ID; Apr. 2017.
Three-Dimensional Graphene Foam for Musculoskeletal Tissue	K. Yocham, C. Scott, K. Fujimoto, E. Tanasse*, J. Oxford, T. Lujan, D. Estrada	Orthopaedic Research Society (ORS) Annual Meeting, San Diego, CA; Mar. 2017.

Graphene Foam as a Bioscaffold for Musculoskeletal Tissue Engineering	R. Brown, C. Scott, A.N. Chang, E. Tanasse*, K. Fujimoto, K. Yocham*, E. Krueger, T. Lujan, J.T. Oxford, D. Estrada	American Advanced Materials Congress, Miami, FL; Dec 2016.
Growth and Differentiation of Myoblasts on Graphene Foam Bioscaffolds	A.N. Chang, Eric Krueger, D. Brown, J. Eixenberg, R. Brown, S. Rastegar, K. Cantley, D. Estrada	Biomedical Engineering Society Annual Meeting, Minneapolis, MN; Oct 2016.
Graphene as a 3-Dimensional Platform for Myotube Growth	E. Krueger, A.N. Chang, D. Brown, J. Eixenberg, R. Brown, S. Rastegar, K. Cantley, D. Estrada	Materials Research Society Electronic Materials Conference, (Newark, DE; Jun 2016
Self-directed channel memristor: operational dependence on the metal-chalcogenide layer	K. A. Campbell	Handbook of Memristor Networks, Ed. L.O. Chua, A. Adamatsky, G. Sirakoulis, Springer, New York, to be published Fall 2018.
Self-directed channel memristor for high temperature operation	K. A. Campbell	Microelectronics Journal, 59, 10-14, 2017
Pulse shape and timing dependence on the spike-timing dependent plasticity response of ion-conducting memristors as synapses	Campbell, Kristy A.; Drake, Kolton T.; and Barney Smith, Elisa H	Frontiers in Bioengineering and Biotechnology, 4, article 97, 1-11, 2016.
Electrical Characteristics of Nanocrystalline Silicon Resistive Memory Devices	S. Gandharava, C. Walker, and K. D. Cantley	Workshop on Microelectronic Devices (WMED), 2017, no. 208, pp. 2–3.

4. **Numbers of Faculty & Students Involved**

In 2015, new software for tracking usage and creating financial reports and invoices was deployed (iLabs). This system enables access to a full set of data (project number, exact usage time and date, etc.) for each time an individual (staff, student, or other) reserves and uses a tool. In FY 2018, the IML exceeded the total FY 2017 student use hours by 40%, following a gain from FY 2016 of 80%. Student usage data since FY 2013 is shown in Figure 4. For FY 2016 through 2018, data shown in Figure 4 is the total number of student use hours (the sum of billed and unbilled hours). Unfortunately, we do not have the number of unbilled hours worked by students prior to implementation of the iLabs software in FY 2015, so those values are only billed hours. The total value also includes hours spent on equipment by student employees either for contract work, qualifying runs, maintenance, etc.

Going further, Figure 4 does differentiate the number of clean room usage hours versus those only on the scanning electron microscope (SEM). Until FY 2016, the IML housed the only high-resolution imaging SEM in the College of Engineering. It thus saw very heavy use by a large number of faculty for a number of years. The IML SEM was decommissioned at the beginning of 2016 following the purchase of a new high-resolution SEM by the Micron School of Materials Science and Engineering, which was placed in the Boise State Center for Materials Characterization. Due to its age, support for the IML SEM from the manufacturer was also extremely limited, which heavily factored into the decision to decommission. Because the IML mission is microfabrication and semiconductor processing, the point to emphasize here is that clean room use for processing (excluding SEM imaging) has been increasing every year since FY 2013.

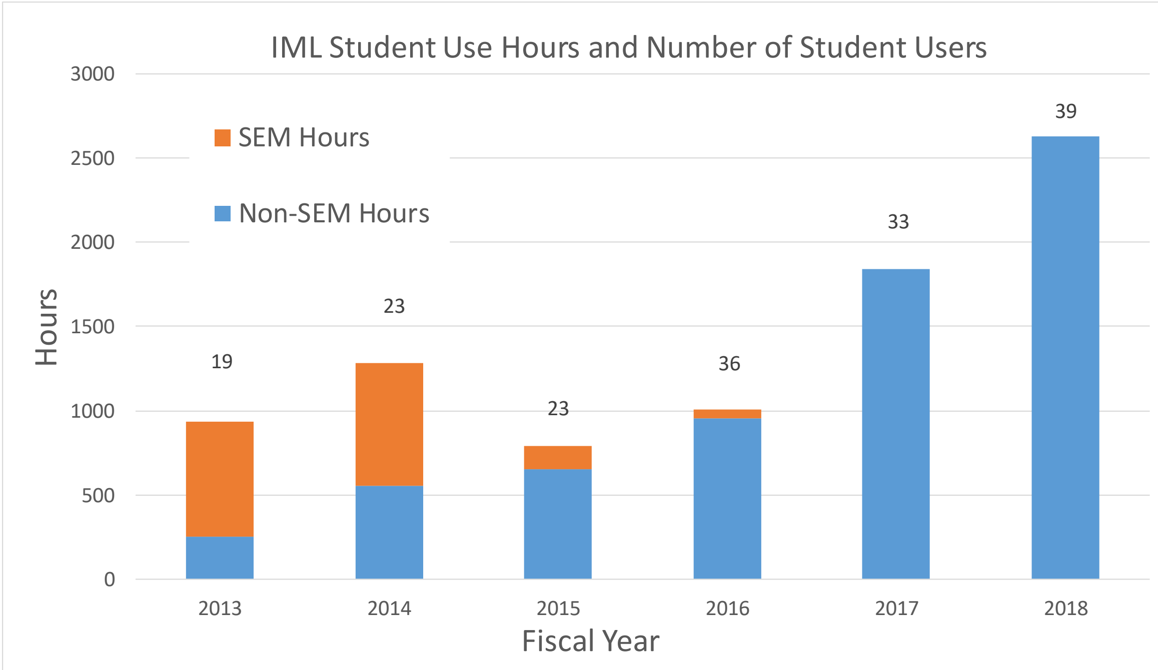

Figure 4. IML student use hours and total number of student users starting in FY 2013. Continuous growth in non-SEM IML usage hours has been occurring for at least six years.

Honors, awards, and internships received by student users of IML are listed below.

- Sepideh Rastegar: 1) Boise State 3-Minute Thesis Winner (2018). 2) Best Poster Award at Workshop on Microelectronics and Electron Devices (WMED), Boise, ID, April 2018. 3) Internship at Micron Technology, Summer 2018.
- Sumedha Gandharava: 1) Best Student Poster Award at International Conference on Neuromorphic Systems (ICONS), Knoxville, TN, July 2018. 2) Internship at Micron Technology, Fall 2017.
- Twinkle Pandhi: 1) NSF Travel Award to Biosensors 2018. 2) 2nd place poster at FLEX 2017.
- Jasmine Cox: Internship at NASA Ames Research Center.
- Tyler Webb: Internship at Air Force Research Laboratory, Wright-Patterson Air Force Base.
- Kiyo Fujimoto: Idaho National Lab Fellowship for Additive Manufacturing of In-Pile Sensors.
- Tony Varghese: Best Poster, 36th International Conference on Thermoelectrics (ICT).
- Binay Joshi: Internship at FiberGuide in Fall 2017.

The number of faculty using the IML is detailed in Section 3.e, with corresponding data shown in Figure 3. Continued growth in the number of faculty users is a strong indicator that the facility is performing efficiently and is readily accessible. Even broader faculty impact can be observed in the list of publication and presentation co-authors in Table 2.

5. **Future Plans for Project Continuation**
   Clean room recharge centers are a unique entity within the university environment. These facilities typically house complex, high-precision equipment with enormous up-front costs, and also require significant back-end investment. This often comes in the form of both infrastructure and tool maintenance. Semiconductor processes employ many hazards, including high power electrical systems, cryogenics such as liquid nitrogen, dangerous compressed gases such as silane, and chemicals including sulfuric and nitric acids, hydroxides, and hydrogen fluoride. Given the potential for harm to users (and bystanders), all safety and protective systems must be maintained and operational at all times. In addition, high-cost equipment inevitably breaks periodically.

   At this time, avenues to continue the kind of broad support of the IML previously provided by IGEM are unclear. Users of the IML will submit major research instrumentation (MRI) proposals with various agencies in support of new equipment acquisitions. Relationships with private donors will also be established with the long-term objective of an endowment fund for the facility. Other support may eventually filter through various state and federal agencies such as the Department of Energy.

6. **Final Expenditure Report (See Attached Template)**

7. **Commercialization Revenue**
   No commercialization revenue was received as a direct result of this project.

8. **Additional Metrics established if applicable (varies by project, must be consistently reported on during each reporting period)**

FINAL EXPENDITURE REPORT

A. FACULTY AND STAFF		
Name/Title	$ Amount Requested	Actual $ Spent
Harish Subbaraman	$87,550	$159,370.02
Travis Gabel	$200,909	$160,716.99
Peter Miranda	$85,000	$72,826.26
B. VISITING PROFESSORS		
Name/Title	$ Amount Requested	Actual $ Spent
C. POST DOCTORAL ASSOCIATES/OTHER PROFESSIONALS		
Name/Title	$ Amount Requested	Actual $ Spent
D. GRADUATE/UNDERGRADUATE STUDENTS		
Name/Title	$ Amount Requested	Actual $ Spent
Sumedha Gandharava Dahl	$26,000	$31,000
Twinkle Pandhi	$26,000	$11,946.20
Pradeep Kumar Kumaradrivel	$26,000	$10,540.40
Binay Joshi	$26,000	$9,150
E. FRINGE BENEFITS		
Rate of Fringe (%)	$ Amount Requested	Actual $ Spent
	$142,292	$152,876.75
PERSONNEL SUBTOTAL:	**$619,751.00**	**$608,426.62**
F. EQUIPMENT: (List each item with a cost in excess of $1000)		
Item/Description	$ Amount Requested	Actual $ Spent
1. Upgrade to PlamaLab System		9,548.50
2. Surface Profile Measuring System		51,057.00
3. Dimatix Materials Printer System		47,025.00
4. General Base Station		48,047.59
5. General Solvent Station		113,514.49
6. Retrofit General Acid Station		30,754.40
7. Zeiss Axio.A1 materials microscope		15,707.20
8. Ion 40 System 115/230V 50/60 Hz Single Phase		43,800.00
9. Optical Table RS2000-58-12 Series		10,107.25
10. Analyzer, FieldFox RF & Microwave		39,674.86
11. Analyzer, Anritsu Optical Spectrum		21,287.28
12. Sputtering Chamber with Pump, Chiller		33,720.00
13. Spectrometer		15,043.32
14. Laser, Wavelength Selectable		11,895.00
15. Glove Box System		10,000.00
16. Prepayment for Plasma Jet Printer		26,500.00
17. Resistivity measurement system		19,790.00
18. Upgrade to Sputtering System		21,105.00
EQUIPMENT SUBTOTAL:	**562,565.93**	**568,576.89**

G. TRAVEL		
Description	$ Amount Requested	Actual $ Spent
1.	0.00	0.00
TRAVEL SUBTOTAL:	0.00	0.00

H. PARTICIPANT SUPPORT COSTS:		
Description	$ Amount Requested	Actual $ Spent
1.	0.00	0.00
2.		
3		
PARTICIPANT SUPPORT COSTS SUBTOTAL:	0.00	0.00

F. OTHER DIRECT COSTS:			
Description		$ Amount Requested	Actual $ Spent
1.Student Fees			31,687.20
2. DektakXT Profilometer			51,057.00
3. 4" SS gate valve, ISO-100F			3,924.00
5. Chilled Water Upgrade			25,000.00
6. Power Meter Kit field optics			1,277.88
7. Static Dissipating chairs for lab			1,899.27
8. Specialized clean room chairs ENGR 105 and 107			1797.00
9. Calibration Kit			1,461.76
10. Cabinet for safe storage of flammables			1,000.00
11. OptiPlex 3020			3,806.88
12. Dell Computers & Laptops			8,209.05
13. Transcat Inc Power Supplies for modulators in MEC 312			2,580.15
14. EJTAUXX502A4 Gold Targets			25,715.00
15. Aerosol Jet Remote Svc Agreement			10,222.50
16. Quality Electric- Electrical Panel			9,260.68
17. Vacuum (S300-T1)			8,782.00
18. Alpha Prototype OEM Plasma Printing			10,232.92
19. JST Acid Wet Bench			30,382.50
20. JST General Base Bench			47,675.70
21. Fuji Dimatix DMP-2831 Materials Printer			47,025.00
22.			
OTHER DIRECT COSTS SUBTOTAL:		329,007.45	323,120.00
TOTAL COSTS (Add Subtotals):			1,5000,000.00
TOTAL AMOUNT REQUESTED:			1,5000,000.00
TOTAL AMOUNT SPENT:			$1,500,000.00