COVER SHEET FOR GRANT PROPOSALS
State Board of Education

SBOE PROPOSAL NUMBER: (to be assigned by SBOE)	AMOUNT REQUESTED: $74,970
TITLE OF PROPOSED PROJECT: Ink Production Scale Up	
SPECIFIC PROJECT FOCUS: The Advanced Nanomaterials and Manufacturing Lab (ANML) at Boise State University has been working on the top-down and bottom-up synthesis of various nanoparticle-based inks. While the inks have demonstrated excellent compatibility with the printers on campus, we are unable to scale-up ink production to satisfy industry needs. In this project, we are requesting funds to support personnel and equipment costs which will enable us to demonstrate ink production scale-up, fostering partnerships with industry to commercialize these inks.	
PROJECT START DATE: 7/1/19	PROJECT END DATE:6/30/20
NAME OF INSTITUTION: Boise State University	DEPARTMENT: Office of Sponsored Programs
ADDRESS: 1910 University Dr., Boise Idaho 83725	
E-MAIL ADDRESS: osp@boisestate.edu	PHONE NUMBER: 208-426-4420

	NAME:	TITLE:	SIGNATURE:
PROJECT DIRECTOR/PRINCIPAL INVESTIGATOR	Dr. Harish Subbaraman	Assistant Professor	Not required
CO-PRINCIPAL INVESTIGATOR	N/A		

NAME OF PARTNERING COMPANY: INFlex Labs, LLC	COMPANY REPRESENTATIVE NAME: David Estrada, CEO

	NAME:	SIGNATURE:
Authorized Organizational Representative	Kimberly Page	Kimberly Page Digitally signed by Kimberly Page Date: 2019.05.28 12:30:41 -06'00'

1. Name of Idaho public institution: Boise State University

2. Name of principal investigator directing the project: Harish Subbaraman, Ph.D.

3. Prior Proposal – This technology has not been proposed and/or been awarded an Incubation Fund Award in the past.

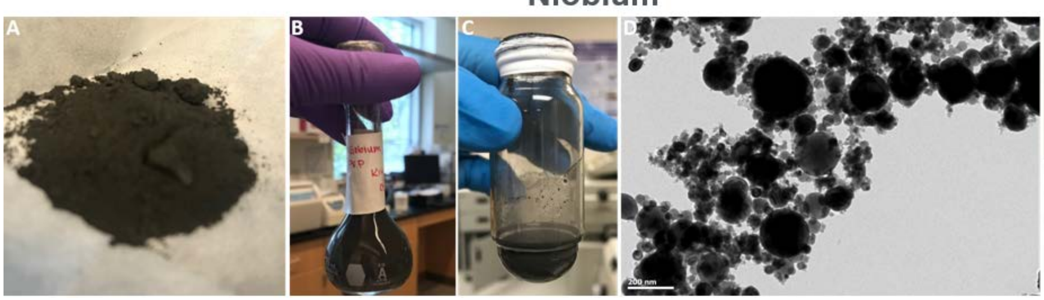
4. Executive Summary – Through this fund, we propose to scale up the synthesis of nanoparticle inks that are currently being developed within our Advanced Nanomaterials and Manufacturing Laboratory (ANML) at Boise State University. Our group has been working on the top-down and bottom-up synthesis of nanoparticle based inks. These include platinum, niobium, cobalt, tungsten, molybdenum, iron, etc, that are not available commercially, and which have recently generated a lot of interest from industry, national laboratories, and government agencies. Ability to scale-up the production volume of these inks will enable us to further foster partnerships with industry, leading to commercialization of these inks and associated technologies.

5. Project Objective and Total Amount Requested – Our project objective is to scale-up the production of nanoparticle inks, thus positioning us to work directly with industry partners to commercialize the inks. We are requesting a total amount of $74,970.

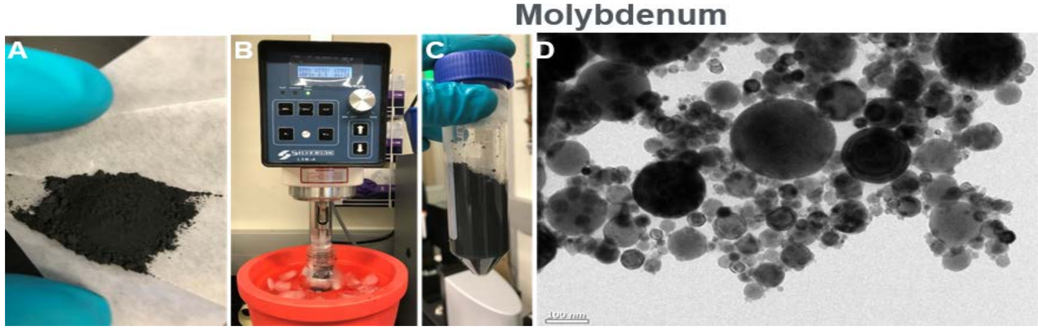
6. Market Opportunity – Over the last decade, additive manufacturing has gained prominence as an alternative method to produce light-weight, flexible, and conformal electronic devices because of features such as large area and high volume manufacturing, low temperature processing, and significantly lower setup and production costs as compared to traditional vacuum-based fabrication techniques. The current market size for printed electronics is $40 Billion and it is expected to rise to $250 Billion by 2025, with applications ranging from consumer electronics, displays, sensors, energy

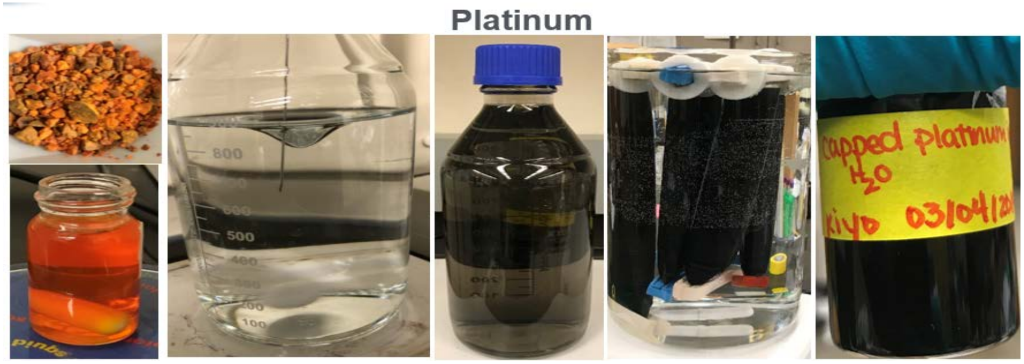
harvesting and storage, healthcare, wearables, etc. Currently, there are very few companies that sell inks compatible with additive manufacturing tools. Moreover, these companies are also restrictive in the types of inks they sell – predominantly silver and copper inks. For various applications, such as in medicine, nuclear energy, space, etc, there is a huge demand for specialty inks, such as those made from nanoparticles of platinum, molybdenum, tungsten, niobium, zinc oxide, etc, which are not currently commercially available. Utilizing the state-of-the-art ink synthesis equipment within the ANML lab, we have developed recipes for ink synthesis and demonstrated small volume synthesis of specialty inks (graphene, platinum, niobium, molybdenum, tungsten, cobalt, iron, alumina, ceria, etc). Examples of Niobium, Molybdenum, and Platinum nanoparticle inks we synthesized are shown below. (Note: ***Invention Disclosures for our inks have been submitted to the Office of Technology Transfer at Boise State).*** We are also in the process of developing inks from nanoparticles of piezoelectric and magnetostrictive materials, which when printed could lead to several novel applications.

Niobium



Molybdenum





This ability to synthesize these inks, although in small quantities, has generated a lot of interest from industry, national labs, and other government agencies. We have specifically been approached by Optomec (manufacturer of Aerosol Jet printers) and Oak Ridge National Lab for our platinum ink capability; NASA Ames for our Zinc Oxide ink capability; Idaho National Lab for our platinum, niobium, molybdenum, tungsten, piezoelectric & magnetostrictive ink capability; American Semiconductor for our platinum ink capability. Ability to scale-up ink production and demonstrating ink reliability and stability are key to sustaining long-term relationships and interest from these public and private entities. Since there is no serious competition at this time for these specialty inks, we believe that this would be an ideal time for us to enter the market. INFlex Labs, LLC (Boise, ID) is identified as Boise State's commercialization partner for inks. This company was co-founded by Dr. Harish Subbaraman and Dr. David Estrada in 2018, upon completion of an IGEM Commerce project and as a way to commercialize technology developed as a part of that Commerce project. Specifically related to this project, INFlex Labs will license technology from Boise State and sell the inks to various customers. Some of the first customers identified include: NASA Ames, Boeing, American Semiconductor, Emerson, Optomec, and Oak Ridge National Lab.

7. <u>The Technology and Path to Commercialization</u> – We will be introducing several novel nanoparticle inks compatible with different additive manufacturing tools for the first time for the printed electronics industry. Currently, we have demonstrated small volume (10-100ml) synthesis of several specialty inks in the lab. Some of these inks, such as platinum, could sell for as much as $10,000 per 100ml. Thus, the ability to scale the volume production of inks will generate substantial revenue earnings for the University and the Business Partner. These specialty inks have a high demand across different industries, national labs, and government agencies. Currently, there are no commercial providers for these specialty inks, thus placing us in a unique position to commercialize them. This unique position has also led to a surge in the number of inquiries our group receives in terms of being a supplier and/or a partner on different proposals. We will be submitting invention disclosures for these inks soon and Boise State will hold the IP rights. These inks were developed in part through funding from the Department of Energy (DOE), National Aeronautics and Space Administration (NASA), and using faculty start-up funds. INFlex Labs, LLC is identified as the first licensee of the ink technology, and will help commercialize these inks. Through our current collaborators and partners, we will explore other application areas and new customers. We have already started talking to printer manufacturers, and we will be working with them to qualify the different inks being developed.

8. <u>Institutional Support</u> – The Idaho Additive Manufacturing Laboratory (IAML) is a dedicated printing facility within the Idaho Microfabrication Laboratory (IML) that is home to three printing modalities – Dimatix Ink-Jet Printing, Optomex Aerosol Jet Printing, and NScrypt Microdispense. In addition, IAML has a suite of film sintering and printed film

characterization equipment. The IAML is one-of-a-kind facility in the nation since it brings different printing modalities within a centralized shared-user facility. The IML also includes a Plasma-Jet Printer, which is currently the only plasma-jet printer in a university across the nation. The IML has a team of paid staff to ensure proper maintenance and working of the printers. The printers on campus cover a very wide range of viscosity and ink property requirements, therefore, compatibility with specific printers could be used to develop inks for any printer in the nation and across the world. Moreover, we have complete ink synthesis and ink characterization capabilities within the ANML, thus allowing us to formulate inks with any desired properties as necessary.

9. <u>Commercialization Partners</u> – As mentioned earlier, INFlex Labs, LLC (Boise, ID) is a small business company co-founded by Prof. Harish Subbaraman and Prof. David Estrada in 2018 with a sole aim to advance and commercialize technologies related to ink synthesis, device printing, and advanced additive manufacturing methods. Commercializing the inks developed through this project is in line with the company's vision, and INFlex will license the ink technology from Boise State. Boise State and INFlex will also work with their current established partners (Optomec, which is the manufacturer of the Aerosol Jet Printing systems; NASA; Boeing; American Semiconductor; Emerson; Oak Ridge National Lab) in further expanding application areas and identifying new customers. For the purpose of this project, the ink synthesis and scaling-up will be performed within the Advanced Nanomaterials and Manufacturing Lab. Ink characteristics, ink reliability and quality will be evaluated at the Idaho Additive Manufacturing Lab facilities on Boise State campus that houses the different printers. With the completion of the Micron Materials Research building in April 2019, new space

will become available, which will enable us to further expand the synthesis process for other material systems. For commercialization, INFlex Labs is working on a user agreement with Boise State so that it can access the ink synthesis and printing equipment. Upon the completion of the project, INFlex Labs (upon licensing the ink synthesis technologies) will be in a position to offer inks to potential customers and commercialize the inks.

10. Specific Project Plan – Our project objectives are specific to demonstrating (a) scaling up of ink volumes and (b) reliable performance of inks for commercial offering through developing partnerships with local industry partners. We have the following tasks planned in the project.

Task 1: Demonstrate increased production volumes of nanoparticle inks.

We are requesting the purchase of a sealed unit shear mixer (Silverson L5M-A-SU), sealed mixing assemblies, square hole and emulsion screens in this project. We have a Tangential flow system in the lab, which will enable particle size reduction and removal of excess surfactants. The shear mixer will enable us to formulate ink quantities over 100ml, up to 4L. We will use established recipes for inks for scale-up as well. Throughout the process for any ink, we will start with small volumes to benchmark performance and identifying suitable solvents and additives that lead to the best ink-substrate combination. We will then aim at increasing the production volume over several iterations, wherein during each iteration, we will closely monitor the ink properties. This will ensure that the results from a previous iteration can be used as the starting point for the next, to achieve the desired volume of ink with the desired properties.

<u>Task 2: Test and record the reliability and repeatability of prepared inks</u>. Testing the consistency of inks and their reliable performance from one batch to another in the production cycle is key to establishing commercial success. Therefore, in this task, we will not only test the reliability of the inks and repeatability of printed features using the developed inks, but also keep detailed records related to the production process and ink test parameters.

Going from one batch to the other, we will check for reliability of the manufacturing process by measuring the rheological parameters of the ink. Using the ink characterization equipment within ANML, we will measure the surface energy, surface tension, composition, nanoparticle size distribution, sintering temperature, etc, from using tensiometer, particle size analyzer, differential scanning calorimeter, viscometer, etc, and % deviation going from one batch to the next will be recorded. In addition, we will purchase a capacitive position sensor and a servo-control module for material characterization. This equipment enables accurate sub-nano displacement measurements piezoelectric and magnetostrictive printed films, thus enabling their properties. The capacitive position sensor will establish new material characterization capability at Boise State University.

We will optimize the ink production process to be within 5% deviation. Inks from each batch will be used to print standard line-space features on a substrate. The printed line width and spacing will be measured and deviation from the designed values will be recorded. The performance of the prepared inks as a function of time will also be determined through performing the abovementioned tests to determine their shelf-life. We will also test the inks on commercial large-scale printers through working with printer manufacturers. For example, Optomec is willing to work with us in testing and qualifying some of our inks with their aerosol jet printing technology.

Task 3: Work with industry partner to commercialize the inks.

The project PI has extensive experience in both using printing technology and in nanoparticle based ink synthesis. The PI, prior to joining Boise State, worked in Industry for seven years on projects related to demonstrating reliable, repeatable, and high-rate printing of electronic devices. He has extensive knowledge regarding the requirements of printers and their associated ink properties. Together, the PI's group has demonstrated the development of several nanoparticle inks compatible with different printers. The group have also demonstrated the development and working of associated printed electronic sensors.

Task Description	**Q1**	**Q2**	**Q3**	**Q4**
Task 1: Demonstrate increased production volumes of inks	⇒	⇒		
Task 2: Test and record the reliability and repeatability of inks		⇒	⇒	
Task 3: Work with industry partner to commercialize the inks			⇒	⇒

11. Criteria for measuring success: As mentioned in Task 2, determining the reliability of inks and repeatability of printed patterns is key to establishing a successful process for scaling-up of inks. Ink rheology metrics, including surface tensions, viscosity, surface energy, sintering temperature, and printed feature dimension repeatability (line and space dimensions) will be used to determine the quality of ink produced in any given batch. The batch will be considered 'meeting specifications' as long as deviations are less than 5%. We will also perform shelf-life characterization of inks and determine the lifetime of inks once the bottle seal is broken.

SUMMARY PROPOSAL BUDGET

Name of Institution: Boise State University

Name of Project Director: Dr. Harish Subbaraman

A. PERSONNEL COST (Faculty, Staff, Visiting Professors, Post-Doctoral Associates, Graduate/Undergraduate Students, Other)

Name/ Title	Salary/Rate of Pay	Fringe	Dollar Amount Requested
PI Dr. Harish Subbaraman; Assistant Professor. 0.10 month. PI Subbarman will manage the Boise State research and be responsible for communication with ISBE and & project deliverables.	$58.05 /hr for 17.33 hours	34%	1,348
Dr. Josh Eixenberger, Post Doctoral Researcher. 1.8 months. Eixenberger will be responsible for nanoparticle synthesis, ink development, and scale up	$26.44/hr for 312 hours	42%	11,715
Undergraduate Research Assistants: 2 student assistants over the academic year and summer. Undergraduates will assist with ink production tasks and testing/analysis.	$12-$13/hr for approximately 600 hrs	4% in the academic year & 10% in the summer	7,705
% OF TOTAL BUDGET: 27.7%		SUBTOTAL:	$20,768

B. EQUIPMENT: (List each item with a cost in excess of $1000.00.)

Item/Description	Dollar Amount Requested
Shear Mixer and heads: This is needed for increasing the ink volume from 10ml to 100ml and more. The benefit to the research is that it will expand our capability in terms of developing and providing new inks for use across different print modalities.	$21,575
Capacitive Sensors: This is needed for testing the quality of piezoelectric and magnetostrictive printed films. The benefit to the research Is that it will provide new capability to Boise State in terms of the inks we can produce	$11,627
	$33,202

C. TRAVEL:

Dates of Travel (from/to)	No. of Persons	Total Days	Transportation	Lodging	Per Diem	Dollar Amount Requested
					SUBTOTAL:	$0

D. Participant Support Costs:	Dollar Amount Requested
1. Stipends	
2. Other	
SUBTOTAL:	$0

E. Other Direct Costs:	Dollar Amount Requested

1. Materials and Supplies: Project consumables for ink scale up. Examples are solvents, surfactants, capping agents, probe tips for sonicators, print heads.	15,000
2. Publication	
3. Consultant Services	
4. Computer Services	
5. Subcontracts	
6. Other (specify nature & breakdown if over $1000) Equipment usage fees for analysis and characterization. This is needed because we need to examine the quality of printed films. Equipment to be used includes SEM, TEM, and Raman.	$6,000
SUBTOTAL:	$21,000
F. Total Costs: (Add subtotals, sections A through E) TOTAL:	$74,970
G. Amount Requested: TOTAL:	$74,970
Project Director's Signature: Not Required	Date: N/A

INSTITUTIONAL AND OTHER SECTOR SUPPORT (add additional pages as necessary)	
A. INSTITUTIONAL / OTHER SECTOR DOLLARS	
Source / Description	Amount
B. FACULTY / STAFF POSITIONS	
Description	
C. CAPITAL EQUIPMENT	
Description	
D. FACILITIES & INSTRUMENTATION (Description)	

FACILITIES, EQUIPMENT, AND OTHER RESOURCES

A. DESCRIPTION OF INSTITUTIONAL ENVIRONMENT

Boise State University's goal of becoming a metropolitan research university of distinction recently reached a major milestone by being designated as a doctoral research institution by the Carnegie Classification of Institutions of Higher Education — the nation's premier college classification system — in 2016. The designation reflects Boise State's unique trajectory in building research and academic programs that the modern economies in fast-growing Boise and the State of Idaho demand. The classification is also a recognition of the university's investment of considerable resources in enhancing research infrastructure, which has resulted in an increase in the number of doctoral programs at Boise State.

The College of Engineering at Boise State University was established in 1997, largely to address workforce and technical expertise needs of the region's high tech economy. It rapidly established itself by setting high academic standards, building a broad research portfolio, and earning accreditation from the Accreditation Board for Engineering and Technology. Since 2004, enrollment among engineering majors has increased nearly 49%, and the college now educates nearly 3000 graduate and undergraduate students. In 2015, nearly half of the college's undergraduate students (46%) earned grade point averages of over 3.0, and the college regularly earns a place on the U.S. News and World Report's list of best undergraduate engineering programs at comprehensive public universities. In 2018, Boise State was ranked 45th in most innovative schools in the nation in rankings published by U.S. News and World Report.

B. BOISE STATE UNIVERSITY USER FACILITIES

IDAHO MICROFABRICATION LABORATORY (IML)

The Idaho Microfabrication Laboratory (IML) is a resource dedicated to the research and advancement of materials and processes used in micro & nanoelectronics design and fabrication. It consists of a small gowning room, a 900 ft^2 Class 1000 cleanroom, a 1500 ft^2 process lab, and a 900 ft^2 metrology lab. The laboratory is equipped to fabricate microelectronic devices using various thin film deposition techniques, chemical processing, photolithography, and plasma etching. All instruments are available to qualified users, and two full-time research technicians support equipment training and maintenance. The university and the state of Idaho have invested heavily to upgrade the facility and add capabilities for additive manufacturing of printed and flexible electronics. The following instruments are available in IML for fabrication and characterization of devices.

MATERIALS PRINTING INSIDE THE IDAHO ADDITIVE MANUFACTURING LAB (IAML)

- Space Foundry Plasma Jet Printer
- Dimatix 2800 Inkjet Materials Printer
- Optomec 200 Aerosol Jet Printer
- nScrypt 3DN Microdispense Printer
- Xenon Sinteron2010 Photonic Sintering

DEPOSITION

- AJA Orion 5 Sputtering Machine
- Torr CrC-150 Benchtop Sputterer
- CHA 600 Thermal Evaporator

CHARACTERIZATION AND METROLOGY

- J.A. Woollam M-2000 Spectroscopic Ellipsometer
- Nanometrics NanoSpec 212
- Bruker Dektax XT-A Stylus Profilometer
- Wyko/Veeco NT1100 Optical Profiler
- Superior Electronics Automatic 4-Point Probe

PLASMA ETCH

- Oxford PlasmaLab 180 ICP with Bosch Etch (fluorine-based)
- Branson 3000 Series RIE/Asher
- Veeco ME-1001 Ion Mill
- Surface Chemistry/Wet Processing
- JST Manufacturing Acid Station with RCA clean
- JST Manufacturing General Base Station
- JST Manufacturing Solvent Processing Station
- SemiTool ST-460 Spin Rinse Dryer

PHOTOLITHOGRAPHY

- Quintel Q-4000 Contact Aligner
- OAI 5000 Contact Aligner
- CEE Model 200X-F Spin Coater (Integrated with JST Solvent Processing Station)

THERMAL PROCESSING

- MiniBrute MB-80 Thermal Oxidation/Diffusion Furnace
- Modular Process Technology RTP-600s Rapid Thermal Annealer
- Blue Electric SV-57A Vacuum Oven
- Programmable Hot Plates (Integrated With Each of Three JST Chemical Processing Stations)
- Systems Integration 7200-1453 Hot Plate

BACK-END PROCESSING

- WestBond Model 7476 Wire Bonding System
- K&S Model 4526 Wedge Bonding System
- ADT982-6 Wafer Dicer

Biomolecular Research Center

Imaging

- Zeiss LSM Meta 510 Confocal Microscope
- SkyScan 1172 MicroCT X-Ray Scanner
- AMG EVOS Fluorescence Microscope
- Zeiss Stemi SV1/M2Bio Microscope
- Olympus BX53 Compound Microscope
- Zeiss Axiovert 40CFL
- Zeiss AxioCam ERc5S digital camera
- Pentax Optio W80 Digital Camera
- Mini-Computer Animated Visualization Environment
- BioRad ProFX Fluorescent Imager
- Life Technologies Countess® II FL Automated Cell Counter
- Nikon TS100/SPOT RT3 camera
- ProteinSimple FluorChemTM R Imager
- Olympus BX53 Microscope
- Olympus BX53-P Polarizing Microscope

Mass Spectrometry Facilities

- Bruker Q-TOF Mass Spectrometer
- ThermoScientific Velos Pro Linear Ion Trap Mass Spectrometer
- Bruker HCT Ion Trap Mass Spectrometer
- MALDI Tandem Mass Spectrometer with Imaging capabilities
- Genius 1050- Nitrogen Generator

Protein Interaction and Determination

- Reichert SR7000 Surface Plasmon Resonance Instrument
- Varian Cary 100 UV/VIS Spectroscopy
- Biotek Synergy H1m Microplate Reader
- Jasco J-810 Circular Dichroic Spectropolarimeter
- VP-ITC High sensitivity Isothermal Titration Calorimeter
- Beckman Proteomix XL-1 Analytical Ultracentrifuge
- TM-Sprayer

Department of Chemistry and Biochemistry

- PupilCAM Megapixel KAM140
- Kodak Gel Logic 200 Imaging System
- ProteinSimple FluorChemE Imaging System
- Eppendorf Mastercycler Real-Time Machine
- Beckman L8-750 Ultracentrifuge

- Agilent 1100 HPLC System
- ThermoScientific Sorvall Legend X1R Refrigerated Benchtop Centrifuge
- ThermoScientific Sorvall ST 16R Refrigerated Benchtop Centrifuge
- NanoDrop 2000C
- Harvey SterileMax Autoclave
- Varian Cary 50 Bio UV/VIS Spectrophotometer
- Varian Cary 100 UV/VIS Spectroscopy
- Cary Eclipse Fluorescence Spectrophotometer
- SynergyHT Multi-Mode Microplate Reader

Transport Characterization Laboratory

The Transport Characterization Laboratory includes three advanced electrical characterization systems and 5 probe stations for measuring electrical properties of materials and devices. One of the probe stations is a custom design closed cycle cryogenic system. The laboratory also houses a state-of-the-art Raman spectrometer to characterize the vibrational characteristics of materials, and an electrical thermometry station for thermal transport characterization.

- 3 Advanced DC & sub-RF Electrical Characterization Systems (Computer Controlled)
- 2 Keithley 4200, 100 aA resolution, dual-channel pulse generator pulse I-V (100 ns rise/fall time and 40-150 ns pulse width, duty cycle: 0.01 to 99% 0-5V, quiescent point pulsing), switch matrix, 20Hz-1MHz C-V, built-in 2-channel 750MHz digital o-scope, Quasi-static CV
- Agilent 4156C semiconductor characterization system with switch matrix
- 3 HP 4284A LCR meters (20Hz to 1MHz)
- Probe Stations: 1 closed-cycle cryogenic with actively cooled probes (5.5 to 450 K), 1 high temperature (673K), 2 room temperature
- Low Noise Spectroscopy System
- Agilent 4294A precision impedance analyzer
- 2 SRS SR830 dual phase and SRS SR810 single phase lock-in amplifiers
- 1GHz 4 channel 4GSamples/s Mixed Signal oscilloscope
- ~25 Cascade micromanipulator probes (4 high temperature)
- Janis CCS-400H/204N high temperature, optical cryostat system with sample in vacuum (10 K to 800 K)
  - 19 pin electrical feed-through
  - LakeShore Model 335 temperature controller
  - Model TS-75-D turbo-pumping station

Boise State Center for Materials Characterization (BSCMC)

Occupying multiple rooms near the Surface Science Laboratory, the Boise State Center for Materials Characterization houses several major pieces of equipment, including both electron-beam and X-ray instruments. Ground-floor laboratory space was renovated in 2009 specifically to house electron beam instruments in ENGR 108 (~650 ft^2, not including a separate service corridor with electrical power, chilled water, vacuum, compressed air, data networking, and a compressed gas distribution system). ENGR 108 currently houses an evaporative coater, a SEM with EBSD and EDS, a FESEM w/NPGS electron beam lithography, and a recently installed EPMA. The equipment, training, and sample characterization are supported to two full-time Ph.D. level staff members. A detailed list of characterization equipment available in BSCMC is provided below:

- JEOL JEM-2100 HR Analytical Transmission Electron Microscope
- Hitachi S-3400N-II Analytical Scanning Electron Microsope
- Bruker AXS D8 Discover X-Ray Diffractometer
- Rigaku Miniflex 600 Benchtop X-Ray Diffractometer
- Leica DM6000 M Materials Microscope
- FEI Teneo Field Emission Gun SEM with Nabity NPGS E-beam Lithography

Surface Science Laboratory (SSL)

The SSL comprises a 600 ft^2 lab (ENGR 104) specifically engineered to provide a constant temperature, low noise environment for optimal AFM and SEM operation. A Herzan VA-2 3-axis accelerometer is available for characterizing and monitoring the vibrational noise spectrum of locations in the SSL. All 3 existing AFMs (see equipment) are located on isolated concrete slabs, situated atop vibration isolation tables and housed in acoustic dampening enclosures. A tabletop touchscreen SEM is also located in ENGR 104 for rapid characterization of samples and AFM probes. To minimize stray light and vibrations. The equipment, training, and sample characterization is supported by a full-time Ph.D. level staff member. A detailed list of equipment available in SSL is provide below:

- Bruker Dimension Icon/FastScan Bio AFM
  - 64 bit Nanoscope V Controller
  - Icon and FastScan Bio AFM heads
  - High speed XYZ closed loop scanning
  - 8 simultaneous real-time data channels (5k x 5k resolution)
  - Thermal stage (-35°C to +250°C)
  - PF-QNM, PF-KPFM, PF-TUNA, and SCM modules
  - MFM, nanolithography, and nanomanipulation capabilities
  - 8” wafer, biological, and multisample chucks
  - Fluid cell
- Bruker MultiMode 8 AFM
  - 32 bit Nanoscope V Controller
  - EVLR vertical engage scanner and ScanAsyst-HR probe holder
  - Herzan TS-140 active vibration isolation table
  - 8 simultaneous real-time data channels (5k x 5k resolution)
  - Thermal stage (room temperature to +50°C)

- PF-QNM, PF-KPFM, PF-TUNA, SCM, and SECPM modules
- Fluid and EC-AFM cells

- Bruker Dimension 3100 AFM
  - Nanoscope IV Controller
  - Hysitron TS 75 Triboscope Nanoindentation System
  - XY closed loop scanner
  - 3 simultaneous real-time data channels (1k x 1k resolution)
  - Thermal stage (-35°C to +250°C)
  - TUNA, CAFM, and SCM modules
  - MFM, nanolithography, and nanomanipulation capabilities
  - 6” wafer sample chuck
  - Fluid cell
- Horiba Scientific LabRAM HR Evolution Raman Microscope
  - 442 nm, 532 nm, and 633 nm (visible) excitation wavelengths available
    - 325 nm (UV) excitation wavelength possible with additional laser line filter
  - 10x, 20x, 50x, and 100x brightfield objectives
    - LWD 20x objective also compatible with DIC, fluorescence, and polarized light
  - 600 and 1800 line/mm holographic diffraction gratings blazed for 500-600 nm
  - 0.8 m monochromator equipped with confocal pinhole
  - Thermoelectrically cooled Si CCD array (256 x 1024) detector
  - ~1 µm lateral resolution at 633 nm (~500 nm maximum resolution with UV excitation)
  - 80 x 100 mm motorized stage for point by point Raman mapping
  - µm step size with ± 1 µm repeatability and accuracy
  - DuoScan optics for high speed, high resolution mapping
- FEI Phenom Tabletop SEM
  - 5 keV source
  - 24x fixed optical magnification
  - 525-240,000x variable electron magnification

TRANSPORT CHARACTERIZATION LABORATORY

The Transport Characterization Laboratory includes three advanced electrical characterization systems and 5 probe stations for measuring electrical properties of materials and devices. One of the probe stations is a custom design closed cycle cryogenic system (5 – 450K). The laboratory also houses a state-of-the-art Raman spectrometer to characterize the vibrational characteristics of materials , and an electrical thermometry station for thermal transport characterization (5 – 850K). A list of detailed characterization equipment available in the Transport Characterization Laboratory is provided below:

- 3 Advanced DC & sub-RF Electrical Characterization Systems (Computer Controlled)
- 2 Keithley 4200, 100 aA resolution, dual-channel pulse generator pulse I-V (100 ns rise/fall time and 40-150 ns pulse width, duty cycle: 0.01 to 99% 0-5V, quiescent point pulsing), switch matrix, 20Hz-1MHz C-V, built-in 2-channel 750MHz digital o-scope, Quasi-static CV
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    - 19 pin electrical feed-through
    - LakeShore Model 335 temperature controller
    - Model TS-75-D turbo-pumping station

College of Engineering (COEN) Student Shop

The student shop is located in the Harry Morrison Civil Engineering (HML) building and supports parts fabrication, machining (including Computer Numerical Control, CNC), welding and painting. The shop is open to students, faculty and staff to work on school-related projects. The state-of-the-art shop has the following machines and capabilities:

- CNC Mill
- CNC Lathe
- Manual Lathe
- Manual Mill
- CNC plasma cutter
- MIG/TIG/ and stick welding capabilities of steel and aluminum.
- Wire EDM
- Solidworks and other CAD/ CAM software
- Capabilities to design and fabricate complex systems.
- 3 Delta style 3D printers with larger print envelop.
- 1 Cube Trio 3D printer

C. PI'S RESEARCH FACILITIES

ADVANCED NANOMATERIALS AND MANUFACTURING LABORATORY (ANML)

Dr. Subbaraman is the director of the Advanced Nanomaterials and Manufacturing Laboratory (ANML) laboratory. The ANML houses a custom built variable pressure chemical deposition system and equipment for liquid exfoliation of 2-dimensional nanomaterials. In addition, a recent infrastructure award from the Department of Energy has allowed the lab to purchase a suite of instruments for nanomaterials ink development. This suite of instruments includes tools for creating nanoparticles and 2D nanoflakes using top-down physical methods, which complement the bottom-up wet chemical nanoparticle synthesis capabilities of the ANML. The addition of a glove box and ultracentrifuge further amplify 2D materials ink synthesis capabilities. A suite of characterization tools will allow for particle size analysis through dynamic light scattering (DLS), and thermophyical properties characterization through thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). A state-of-the-art tensiometer will also allow for characterization of ink-substrate interactions, e.g. wettability and surface tension.

A detailed list of equipment available at ANML for material synthesis and material solution formulation is provided below:

- Axon MultiClamp 700B patch clamp amplifier on a vibration isolation table
- Axon Digidata 1550 low-noise data acquisition system
- pClamp 10 electrophyisology data acquisition and analysis software
- Custom built quartz tube variable pressure chemical vapor deposition system with 4 inlet gases and up to two solid-source precursors.
- QSonica Q125 probe-tip ultra-sonicator
- QSonica Q700 probe-tip ultra-sonicator
- Branson 2800 variable temperature ultra-sonicator
- 6 Eppendorf adjustable volume pipettes
- 6 Fisherbrand mini-centrifuges
- Mettler Toledo Analytical Balance
- Thermo Scientific Legend Micro 21 Microcentrifuge
- Think Planetary Centrifuge
- Thermo Scientific Heratherm Programmable Gravity Convection Oven
- Heraeus Megafuge 8 with TX-150 Cell Cult Pkg (8 x 50 ml)
- MTI 2" Quartz Tube furnace with inert gas inlet and vacuum compatible
- Agilent and Varian Eclipse Fluorescence Spectrophotometers
- Agilent Cary 5000 UV-Vis-nIR spectrophotometer
- COMSOL Multiphysics FEM software
- MBraun UniLab Pro PS Glovebox System
- Retsch EMAX High Energy Ball Mill System
- Beckman/Coulter Optima XE-90 Ultracentrifuge w/SW41 Rotor

- Labconco FreeZone 4.5L Benchtop Freeze Dryer w/PTFE Coated SS 12 Port Drying Chamber
  (-105 °C)
- Biolin Scientfic T200-Auto3 Attension Theta Optical Tensiometer with Automatic XYZ stage and Pipette Dispenser
- Brookhaven NanoBrook Omni Submicron Particle Sizer (DLS) and Zeta Potential Analyzer (PALS)
- Netzsch STA 449 F5 Jupiter Simultaneous Thermal Analyzer (TG-DSC/DTA; RT to 1600 °C)
- Zeiss Axio Imager M2m Materials Microscope
  - Transmitted Light
  - Reflected Light
  - DIC imaging
  - Phase Contrast Imaging
  - Automated X-Y-Z mechanical Stage
  - Axiocam 105 Colar Camera
  - 10X thru 100X objectives
- Brookfield Engineers Lab DV3TLV Rheometer
- Biocomp Instruments Nano Gradient Fractionator/Former
- Buchi Corporation Rotavapor R-100 Rotary Evaporator with I-100 Controller

PROFESSIONAL PREPARATION

INSTITUTION	LOCATION	MAJOR	DEGREE & YEAR
Chaitanya Bharathi Institute of Technology	Hyderabad, India	Electronics and Communication Engineering	B.E., 2004
The University of Texas at Austin	Austin, TX	Electrical Engineering	M.S.E., 2006
The University of Texas at Austin	Austin, TX	Electrical Engineering	Ph.D., 2009

APPOINTMENTS

PERIOD	APPOINTMENT	INSTITUTION & LOCATION
2016–Present	Assistant Professor	Boise State University, Boise ID
2012-2016	Senior Research Scientist	Omega Optics, Inc, Austin, TX
2009-2012	Research Scientist	Omega Optics, Inc, Austin, TX

PRODUCTS

1. P. M. Grubb, H. Subbaraman, S. Park, D. Akinwande, and R. T. Chen, "Inkjet Printing of High Performance Transistors with Micron Order Chemically Set Gaps," Scientific Reports, **7**: 1202 (2017)
2. C. Zhang, H. Subbaraman, Q. Li, Z. Pan, J.G. Ok, L. Tao, C. -J. Chung, X. Zhang, X. Lin, R. T. Chen and J. Guo, "Printed Photonic Elements: Nanoimprinting and beyond," J. Mater. Chem. C, 5133-5153 (2016)
3. W Li, Y. Hei, H. Subbaraman, X. W. Shi, and R. T. Chen, "Novel printed filtenna with dual notches and good out-of-band characteristics for UWB-MIMO applications," IEEE Microwave and Wireless Components Letters, vol.26, pp.765-767 (2016).
4. X. Lin, H. Subbaraman, Z. Pan, A. Hosseini, C. Longe, K. Kubena, P. Schelicher, P. Foster, S. Brickey, and R. T. Chen, "Towards realizing high-throughput, roll-to-roll, manufacturing of flexible electronic systems," Electronics, vol. 3, pp. 624-635 (2014)
5. H. Subbaraman, D. Pham, X. Xu, M. Y. Chen, A. Hosseini, X. Lu, and R. T. Chen, "Ink-Jet Printed Two Dimensional Phased-Array Antenna on a Flexible Substrate," IEEE. Antennas and Wireless Propagation Letters, vol. 12, pp. 170-173 (2013)
6. X. Lin, T. Ling, H. Subbaraman, X. Zhang, K. Byun, L. J. Guo, and R. T. Chen, "Ultraviolet imprinting and aligned ink-jet printing for multilayer patterning of electro-optic polymer modulators," Optics Letters, vol. 38, pp. 1597-1599 (2013)
7. D. Pham, H. Subbaraman, M. Y. Chen, X. Xu, and R. T. Chen, "Self-Aligned Carbon Nanotube Thin-Film-Transistors on Flexible Substrates with Novel Source-Drain Contact and Multi-layer Interconnection," IEEE. Trans. Nanotech, vol. 11. no. 1, pp. 44-50 (2012)
8. M. Y. Chen, D. Pham, H. Subbaraman, X. Lu, and R. T. Chen, "Conformal Ink-jet Printed C-band Phased-Array Antenna Incorporating Carbon Nanotube Field-effect Transistor Based Reconfigurable True-time Delay Line," IEEE Trans. Microwav. Theory. Tech, vol. 60, no. 1, pp. 179-184 (2012)
9. G. Gu, Y. Ling, R. Liu, P. Vasinajindakaw, X. Lu, C. Jones, W.-S. Shih, V. Kayastha, N. Downing, X. Han, H. Subbaraman, D. Pham, R. T. Chen, M. Y. Chen, U. Berger and M. Renn, "All-Printed Thin-film Transistor based on Purified Single Walled Carbon Nanotubes (SWCNT) with Linear Response," J. Nanotechnology, vol. 2011, 823680 (2011)

10. J. Vaillancourt, H. Zhang, P. Vasinajindakaw, H. Xia, X. Lu, X. Han, D. C. Janzen, W.-S. Shih, C. S. Jones, M. Stroder, M. Y. Chen, H. Subbaraman, R. T. Chen, U. Berger, and M. Renn, "All ink-jet-printed carbon nanotube thin-film transistor on a polyimide substrate with an ultrahigh operating frequency of over 5 GHz," Appl. Phys. Letts, vol. 93, pp. 243301 (2008)

SYNERGISTIC ACTIVITIES

Reviewer— Scientific Reports, Applied Physics Letters, Optics Express, AIP Advances, Optics Letters, Applied Optics, Electronic Device Letters, IEEE Photonics Technology Letters, IEEE Transactions of Microwave Theory and Techniques (IEEE-MTT), IEEE Journal of Selected Topics in Quantum Electronics, Sensors and Actuators: B, Optical Engineering, Chinese Optics Letters, Current Nanoscience.

Co-Guest Editor – Electronics Journal - Special Issue on Flexible Electronics (MDPI).

Chair, 2019 CLEO Session on Beamforming and Free-Space Optics; 2017 IEEE Workshop on Microelectronic Devices (WMED) Invited Tutorials

Graduate Advisor and Mentor – 3 graduate students and 5 undergraduate students

Co-supervisor, Student Research— Daniel Pham (Ph.D., 2010), Xiaochuan Xu (Ph.D., 2013), Xiaohui Lin (Ph.D., 2013), and undergraduate REU researcher John Binion (2013).

Technical Program Committee Member - Optoelectronic Devices and Integration IV, 5 November 2012; Optoelectronic Interconnects XII, 21 January 2012; Optoelectronic Devices and Integration III, 18 October 2010, Beijing, China.

CURRENT PROJECTS

TITLE	SPONSOR	AMT	PERIOD	MOS.
Integrated Silicon/Chalcogenide Glass Hybrid Plasmonic Sensor for Monitoring of Temperature in Nuclear Facilities	US Department of Energy	712,000	10/1/17-9/30/20	1.0
Space Grade Flexible Hybrid Electronics	University of Idaho/NASA	586,746	8/6/17-8/5/20	0.6
Measurement of Structure and Chemistry of Fuel Surrogates Using Electrochemical Impedance Spectroscopy and IR Thermography	Battelle Energy Alliance/DOE	209,250	8/16/18-9/30/19	0.25
Nuclear Instrumentation	Battelle Energy Alliance/DOE	465,000	9/4/18-9/30/19	0.20
Collaborative Research: Direct, Clog-Free Printing of Functional Nanomaterials Using Nozzle-Free Ultrasound Cavitation	National Science Foundation	187,132	9/1/18-8/31/21	0.15
Work Package 4: Advanced Manufacturing for In-Pile Nuclear Sensors	Battelle Energy Alliance/DOE	376,027	8/3/17-9/30/19	0.25

INFlex Labs, LLC.

Materials and Technology for a Flexible World

May 20th, 2019

Harish Subbaraman
Assistant Professor
Electrical and Computer Engineering
Boise State University
1910 University Dr
Boise, ID 83725

Dear Dr. Subbaraman,

INFlex Labs, LLC is excited to support your proposal to the Idaho Higher Education Research Council IGEM Incubation Fund program entitled *Ink Production Scale Up*. The global printed and flexible electronics industry is rapidly growing and projected to reach $250B by 2025. A major bottle neck in this industry is the availability of high quality materials to tailor the electrostatics of printed electronic devices – e.g. workfunction matching for photodetectors, transistors, and diodes.

We are excited about the work ongoing in the Advanced Nanomaterials and Manufacturing Laboratory at Boise State University and look forward to working with you and the university as a commercial partner to scale up production of your nanoparticle based inks. One of the major foci of INFlex Labs, LLC is in providing novel materials to the printed and flexible electronics industry, and this partnership is a natural fit for our nanoparticle based ink commercialization goals.

Yours sincerely,

David Estrada

David Estrada, Ph.D.
Co-Founder & President

3986 S. Oak Brook Way | Boise, ID 83706 | 208.860.6035 | daveestrada@inflexlabs.com

6987 W Targee St
Boise, ID 83709
208.336.2773

May 21st, 2019

Harish Subbaraman, Ph. D.
Department of Electrical and Computer Engineering
Boise State University

Dear Dr. Subbaraman,

I am pleased to support your *Ink Production Scale Up* proposal for submission to the Idaho HERC Incubation Fund. We are looking forward to seeing you being able to scale-up the production of some of your inks, especially platinum, piezoelectrics, and magnetostrictives. For American Semiconductor and the general printed electronics market, availability of the inks you are developing would benefit applications in wearable electronics, stretchable electronics, structural health monitoring, Internet of Things sensors, biomedical sensors, and rapid electronics prototyping. For our target markets, we see additive manufacturing having the potential to enable new electronics solutions and applications through and supplement our FleX™ Semiconductor-on-Polymer™ IC technology:

1. Multi-material printing (conductive interconnects – traditional and stretchable, dielectrics, protective coatings, and more) for flexible hybrid electronics (FHE) system manufacturing
2. Advanced printable sensors for integration with our FleX-ICs to create new and novel FHE electronics systems
3. Energy harvesting for ultra-low power system operation without batteries and extending the operation of distributed FHE sensor systems

American Semiconductor is an industry leader in flexible integrated circuits and flexible hybrid electronics (FHE) development. Throughout our 18-year history, we have worked closely with Idaho universities. Working with Idaho universities is consistent with American Semiconductor goals of (1) advancing US-based high technology design and manufacturing, (2) supporting STEM education, and (3) identifying and recruiting highly capable engineers to join our team.

As an on-shore, ITAR compliant, flexible electronics products and services provider, American Semiconductor supports all aspects of IC design, FleX™ Silicon-on-Polymer™ flexible wafer processing, and Flexible Hybrid Systems design & manufacturing. Engineering support for flexible hybrid systems includes printed electronics design and fabrication, antenna design and fabrication, FleX integration, prototype development, and production. For this program, we will provide our advanced FleX ICs, FHE engineering services and intern training. In conclusion, we fully support the project goals you have established for this *Ink Production Scale Up* proposal. We look forward to collaborating with you in the application of your inks to the design, manufacturing and testing of new electronics devices and in training up a new generation of flexible electronics engineers.

Sincerely,

Dale G. Wilson
Director of Engineering

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, CA 94035-1000

May 17, 2019

Idaho Education Board
Boise, ID

Dear Board Member:

I am writing this letter in support of the application by Prof. Harish Subbaraman to the HERC Incubation Fund on the synthesis of various inks for printed electronics. I have known Prof. Subbaraman nearly four years and collaborated with him during this period. In fact, I have helped him recently to get a 3-year NASA EPSCOR funding in printed electronics.

Internet of Things (IoT) is a rapidly emerging technology with potential to create multi billion global commercial market in the very near future. Indeed, there are numerous US companies - both large and startups - vying for market share in addition to US government funded NextFlex consortium tasked with creating a US ecosystem for printed and flexible electronics which will provide the various hardware (sensors, RFID, antennas, thin film circuits, printed batteries etc.) to enable IoT. These devices are typically printed on flexible substrates such as plastics, paper and textile using ink jet printing and other competing techniques. The biggest bottleneck right now is the lack of availability of suitable inks for conductors, semiconductors and dielectrics. Very few commercial sources exist - both US and foreign - most with questionable quality. Thus, the application by Prof. Subbaraman is extremely timely and meant to rectify the problem with high quality printable inks of various important materials of value to IoT. He brings unique expertise to tackle this problem.

Finally, successful completion of the project has exceptional market potential due to the staggering impact expected of IoT. The project can lead to licensing of IP from Boise State by multiple stakeholders and/or startup companies springing in Idaho. Therefore, I highly recommend this application for your funding consideration.

Yours truly,

Meyya Meyyappan, PhD
Chief Scientist for Exploration Technology

May 21st, 2019

RE: HERC Incubation Fund

To: Idaho State Board of Education HERC

I am pleased to support Dr. Harish Subbaraman's HERC Incubation Fund proposal titled "Ink Production Scale Up," which aims to increase the production volumes of several electronic-grade inks made from specialty nanoparticles, such as platinum, tungsten, etc. I strongly endorse this project as it will contribute new inks that will contribute substantially to our In Space Manufacturing efforts ongoing at NASA Marshall Space Flight Center. I am willing to provide guidance on ink development and overall project goals and objectives.

Sincerely,

Curtis W. Hill

Senior Materials Engineer and Subject Matter Expert, In Space Manufacturing
NASA Marshall Space Flight Center
Huntsville, AL. 35801
256-655-6876
curtis.w.hill@nasa.gov