# 2019 REPORT

# RESEARCH TRIANGLE NANOTECHNOLOGY NETWORK

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National Nanotechnology Coordinated Infrastructure


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# ABOUT RTNN

Nanotechnologies are currently in development for use in diverse fields. These technologies take advantage of unique properties achievable at the nanometer ($10^{-9}$ m) scale to tackle complex problems (e.g. make more efficient solar panels or deliver cancer therapeutics). To support and expand the growth of nanotechnology, the National Science Foundation (NSF) established the National Nanotechnology Coordinated Infrastructure (NNCI) in 2015. The NNCI is made up of 16 sites across the US whose work is focused on the development and analysis of unique nanotechnologies. The Research Triangle Nanotechnology Network (RTNN) is one of such sites.

The RTNN is a collaborative partnership between North Carolina State University (NC State), the University of North Carolina at Chapel Hill (UNC), and Duke University (Duke). Collectively, these institutions house eight open-access nano-fabrication and characterization facilities and over 100 principal faculty members whose research encompasses broad aspects of nanotechnology. The overarching goal of the RTNN is to dramatically enhance access to university nanotechnology resources, such as fabrication and characterization facilities and techniques as well as expert research personnel, by lowering barriers to access such as distance, cost, and awareness. Through its activities, the RTNN is able to support and advance basic research at the nanoscale as well as development and commercialization of innovative nanotechnologies.

## Program Highlights

Our activities are designed to raise awareness of our nanotechnology facilities and their capabilities as well as how they can be accessed. These activities are innovative, comprehensive, and effective with **continual assessment and revision** by Professor David Berube and his team. Highlights from 2019 include:

- More than **1,500 unique annual users** accessed RTNN facilities for **over 61,000 hours** of experimental time, an increase of 10 percent from the previous year
- **Community college faculty members** fabricated an LED device in the clean room and developed new curriculum at RTNN's annual educator workshop
- ***Nanotechnology: A Maker's Course***, a Coursera on-line course, enrolled >5,300 learners in >155 countries
- **The Kickstarter program** provided ~150 hours on nanotech tools to 15 non-traditional and new users
- RTNN visited regional schools, libraries, and museums to give more than 1,800 people training and hands-on experiences like operating a **portable scanning electron microscope (SEM)**
- **11 educators in the Atomic Scale Design and Engineering RET Program** engaged in nanotechnology research projects at RTNN institutions and developed novel lesson plans grounded in their work
- **More than 3,500 K-Gray participants** were reached with **1,500 engaged in hands-on programs** within the facilities. Greater than 60 percent of participants were from underrepresented groups in STEM

## VISION

The vision of the RTNN is to be a national focal point for enabling innovative nanoscience and nanotechnology research, discovery, workforce development and education through

- Open access to an evolving and integrated suite of cutting-edge fabrication and characterization facilities
- Engagement of faculty and user populations with diverse research expertise to support the development of new processes, tools, and instrumentation
- Innovative training programs, outreach, and meetings/workshops to reach and educate new user populations

# CORE FACILITIES

The RTNN provides a broad foundation of core technical capabilities in nanotechnology fabrication and characterization. The RTNN also contributes unique expertise and facilities in the areas of "soft, wet" materials (e.g., textiles, plants, and biological nanomaterials), heterogeneous integration, and in situ characterization.

AIF analytical instrumentation facility

**Analytical Instrumentation Facility (AIF**) provides nano-characterization of both hard and soft materials and has over 9 in situ stages (liquid cells, heating, mechanical loading, electrical biasing) for microscopy and diffraction.

CHANL MAKE NANO – MEASURE NANO

**Chapel Hill Analytical and Nanofabrication Laboratory (CHANL)** offers standard and specialized nanofabrication and characterization capabilities including rapid prototyping of nano- and microstructures in a variety of substrate materials.

NNF

**NC State Nanofabrication Facility (NNF)** operates in a class 100/1000 cleanroom, which houses a comprehensive toolset for deposition, etching, and patterning of nano- and micro-devices and structures with additional space dedicated to characterization.

SMiF

**Shared Materials Instrumentation Facility (SMIF)** offers a comprehensive fabrication and characterization facility with unique cleanroom fabrication and characterization capabilities for research in bio/soft matter nanoscience, environmental nanotechnology, heterogeneous integration, and metamaterials/ plasmonics.

## BY THE NUMBERS

- **3** major research universities
- **8** open-access user facilities
- More than **40,000** sq. ft. of laboratory space
- More than **230** major fabrication and characterization tools
- More than **65** technical staff members
- More than **61,000** annual hours of collective use



# AFFILIATED FACILITIES

**The Chemical Analysis and Spectroscopy Lab (CASL)** offers a full range of instrumental and classical wet chemistry techniques, including gas, ion, and liquid chromatography. CASL's services provide solutions to problems aimed at raw materials testing, chemical impurities, solvent testing, and more.

**The Zeis Textile Extension Education for Economic Development Center (ZTE)** provides professional education and services including hands-on training for all aspects of textile processing. Within ZTE, The Textile and Forensic Analytical Laboratory offers comprehensive chemical analysis of nanofibers, dyes, and other associated chemistries.

**The NC State Nuclear Reactor Program** provides non-destructive testing and characterization of materials using neutron imaging, neutron powder diffraction, the intense positron beam, and neutron activation elemental analysis.

**The Duke Magnetic Resonance Spectroscopy Center (DMRSC)** offers ultra-high-field NMR instruments with cryogenically cooled probes as well as conventional instruments.

**Public Communication of Science and Technology (PCOST)** is a social science laboratory coordinating research on issues in science and engineering. Its membership is diverse and study subjects include methods appropriate to assess laboratory activities, public understanding of the risks of zoonic diseases, and climate change communication.

## Specialized Equipment and Expertise

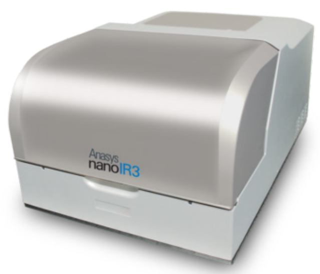
In addition to providing a strong foundation of fabrication and characterization facilities and capabilities, the RTNN offers highly specialized nanotechnology fabrication and characterization equipment and expertise. Representative examples of these unique capabilities:

- Hot embosser
- Electrospinning of nanofibers
- High temperature furnaces for SiC
- Positron annihilation spectroscopy
- Small-angle X-ray scattering (SAXS)
- Extreme-resolution scanning EM (SEM)
- Vibrational microscopy
- In situ (heating, gas, and liquid stages) transmission EM (TEM)
- Chemically-sensitive, atomic-resolution scanning TEM (STEM)
- Cryo-TEMs for biological and soft materials imaging and single particle analysis
- High-Resolution NMR spectroscopy
- X-ray Microscopy

# NEW TOOLS AND CAPABILITIES

Through the support of our universities and by leveraging external funding proposals, the RTNN has acquired and/or upgraded >45 tools valued at >$12.6 million. The equipment was selected through discussions with users, principal investigators, and long-term strategy of the facilities. In 2019, several new pieces of equipment were acquired.

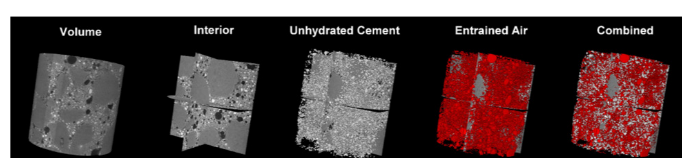
- **The Bruker nanoIR3 nano-infrared spectrometer** (NSF MRI Award, PI Scott Warren, UNC Department of Chemistry) combines IR microscopy with an atomic force microscope (AFM) to measure IR spectra with a spatial resolution of approximately 10 nm. This new tool allows the composition of heterogeneous surfaces to be studied such as the distribution of proteins on the surface of cells or the interfaces in organic photovoltaics. This new capability is allowing complex surfaces to be measured, such as the electrode/electrolyte interface in batteries, where the composition varies on the 10-nm length scale. The ability to discern spatial variations in the chemical functionality of battery electrodes will allow fundamental insight into, for example, mechanisms of degradation. The uses of the nano-IR spectrometer extend beyond measuring functional groups to applications from nanophotonics to electrochemistry to cellular biology.



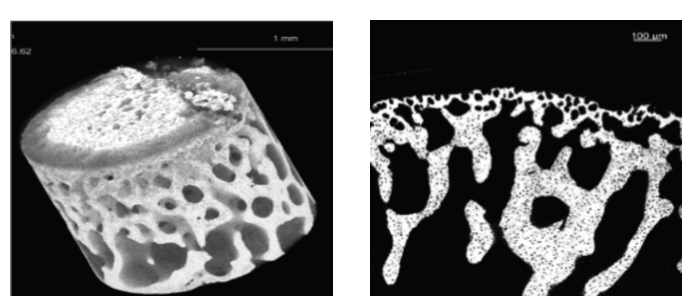
Bruker nanoIR3 nano-infrared spectrometer

Zeiss Xradia 510 Versa X-ray Tomography System

- **The Zeiss Xradia 510 Versa High-Resolution 3D X-ray Tomography System** acquired through an NSF MRI award (PI Jacque Cole, NC State and UNC Joint Department of Biomedical Engineering) has the following unique characteristics for nondestructive, quantitative, three-dimensional characterization of a wide range of sample sizes and material types:
  - **Dual-stage detector system:** The unique detector system has two-stage magnification geometry that includes both optical magnification and X-ray projection geometric magnification, providing high spatial resolution at large working distance. It has a maximum spatial resolution of 700 nm with a minimum achievable voxel size of 70 nm.
  - **Detector variety:** Four detectors are installed to provide a wide range of spatial resolution, including large field of view (0.4x), low resolution (4x), ultra-high resolution (20x), and large volume imaging (FPX). The FPX accommodates larger samples to enable versatile multi-scale workflows.
  - **Absorption contrast and phase contrast modes:** Enhanced absorption contrast detectors maximize collection of low-energy photons to optimize contrast of materials with low atomic number or similar atomic number, such as soft tissues and polymers. Tunable prophase contrast measures refraction of X-ray photons at material transitions to visualize features with little or no contrast.




3D images of a cement sample during the curing process from the Xradia X-ray microscope. Courtesy of Laura Dalton.



X-ray microscopy examination of microstructural defects in cortical bone due to brachial plexus birth injury. Courtesy of Katie Baldridge.

- **The Thermo Scientific Talos F200X** scanning/transmission electron microscope (S/TEM) combines outstanding high-resolution S/TEM and TEM imaging with industry-leading energy dispersive x-ray spectroscopy (EDS) signal detection and 3D chemical characterization with compositional mapping. The Talos F200X S/TEM allows for the fastest and most precise EDS analysis in all dimensions (1D-4D) along with the best HRTEM imaging with fast navigation for dynamic microscopy. The Talos F200X S/TEM does all this while also providing the highest stability and longest uptime.

Talos F200x

- **The Disco DAD323 is a highly versatile automatic dicing saw** capable of dicing a range of semiconductors in addition to glass, ceramics, and other hard-to-cut materials. It is able to support workpieces as large as 6-inch square wafers.

Disco DAD323 Dicing Saw

- **The Leica EM ACE900** can perform freeze fracture, freeze etching, and e-beam coating in one instrument. The instrument is equipped with a load lock and gate valves, so the instrument can always stay under vacuum ensuring fast and clean working conditions. The system is utilized in sample preparation for TEM and cryo-SEM analysis. These techniques are ideal for maintaining the integrity of soft material samples, like biologicals.

Leica EM ACE900

- **The Tousimis Autosamdri-931 Critical point drier** dehydrates samples by replacing the liquid in the sample with liquid $CO_2$ and then slowly raising the temperature above the critical temperature to change the liquid $CO_2$ to a vapor without a change in density, thus eliminating the surface tension effects that would distort the morphology and structure. Typically used for preparing biological samples for electron microscopy, critical point driers have also been used to dry MEMs devices or other high aspect ratio features without collapse. The Tousimis Autosamdri-931 is a fully automated system allowing for more reproducible sample preparation. It can operate in two modes: a slow fill option that protects more delicate features during the drying process and a stasis mode for drying thick samples including gels.

Tousimis Autosamdri-931 Critical point drier

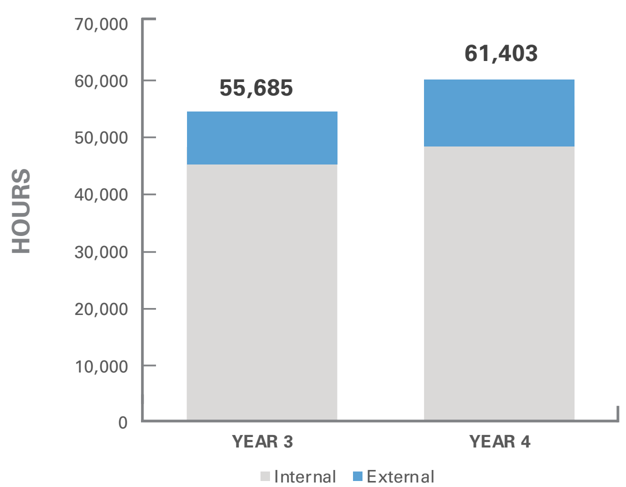
- **The Hitachi TM-3030Plus** is a compact desktop Scanning Electron Microscope. It is capable of imaging in secondary and backscattered electron modes using accelerating voltages of 5kV or 15kV. A rolling cart, tie down straps, and a protective cover were also purchased that enable easy transportation to other locations. This SEM is being used extensively in educational and outreach activities at schools, libraries, and museums.

Hitachi TM-3030 Plus desktop SEM

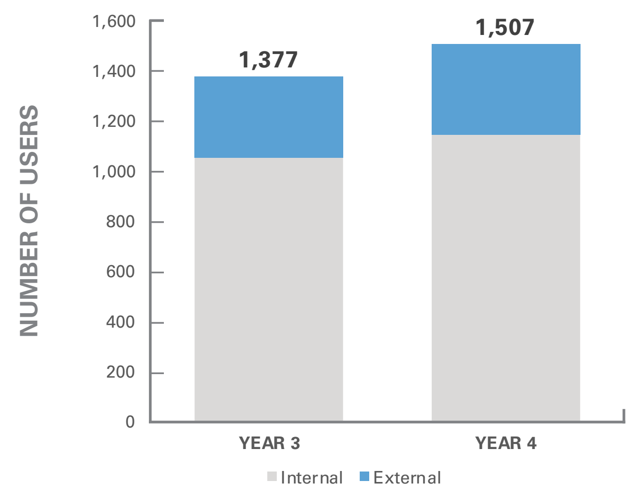
# WHO USES RTNN?

In 2019, more than 1,500 unique users accessed the facilities for over 61,000 hours, increases of 9 and 10 percent, respectively, from the previous year. During this time, the RTNN trained more than 600 new users. RTNN currently draws the majority of its users from the host institutions (76 percent) and greater than 85 percent of the use is on-site. These users come from a broad range of disciplines including non-traditional disciplines such as the life sciences and medicine. Our efforts to increase the number of external users and their time in the facilities has been fruitful, with external researchers growing from 323 to 363 and their hours growing from 9,249 to 11,719 over the past year.

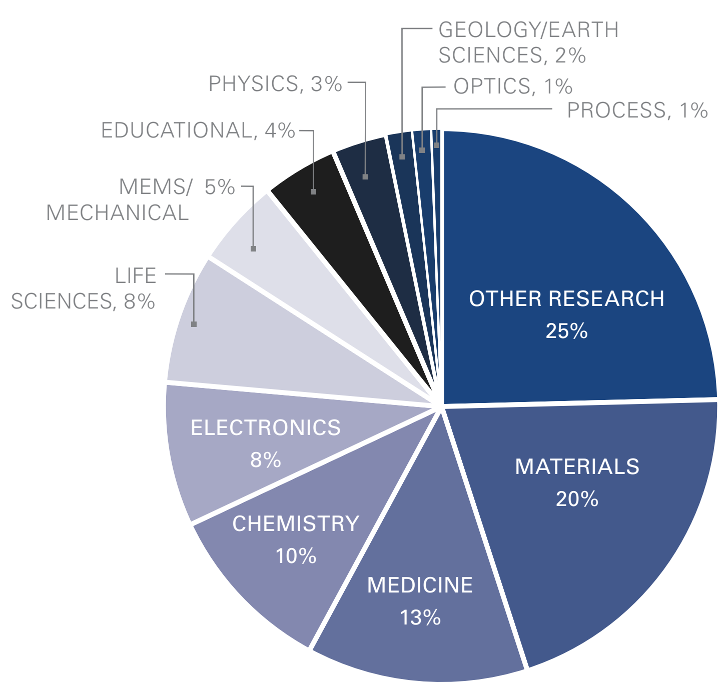
## LAB TIME IN RTNN FACILITIES



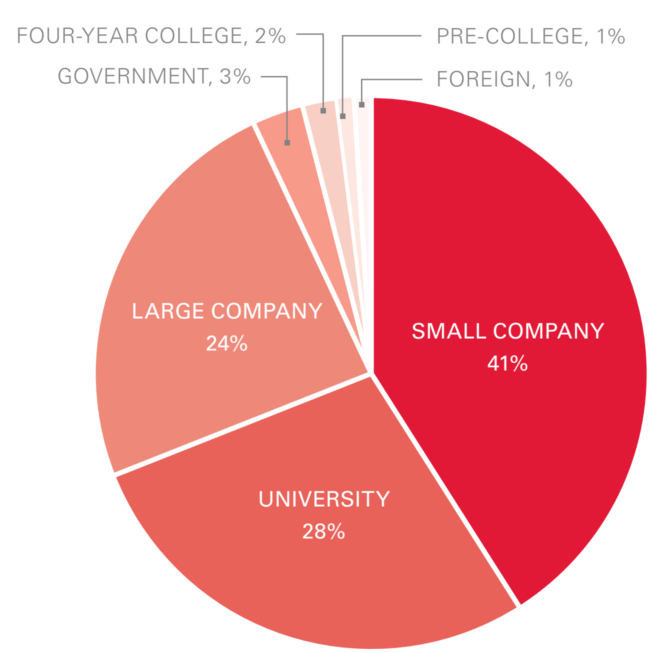

## RTNN CUMULATIVE USERS




## ALL USERS BY DISCIPLINE




## EXTERNAL USERS BY AFFILIATION




# EXTERNAL USER HIGHLIGHT: KYMA TECHNOLOGIES

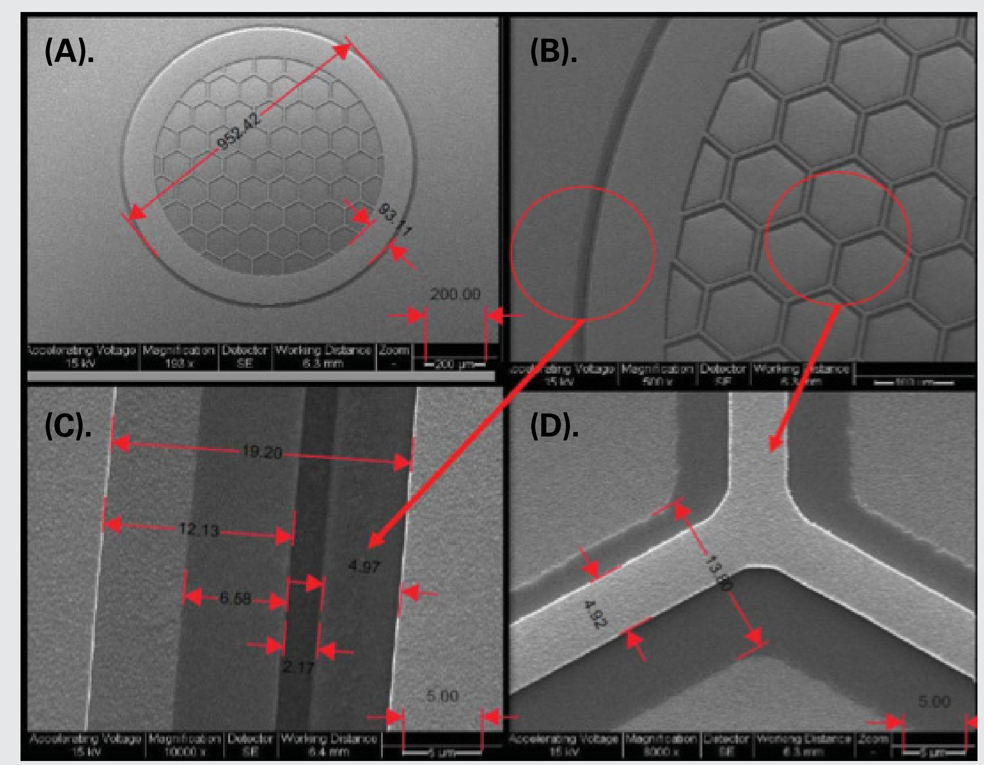
### Development of Transmissive III-Nitride Semiconductor Electrodes for Next Generation Solid State Photomultiplier Detectors

*Device Process Engineer: Jaime A. Rumsey*
*PI: Jacob H. Leach (CTO)*
*Kyma Technologies, Raleigh NC*

Kyma supports the Nevada National Security Site (NNSS) in its pursuit of next generation photodetectors. Detectors for high-energy gamma and neutron prompt diagnostics are critical technologies for many applications at the NNSS and elsewhere. Unfortunately, legacy, high-quality standard photomultiplier tube technology is becoming outdated and difficult to maintain. This project addresses an ongoing need to move toward more advanced solid-state detector concepts. In the first year of this effort, Kyma helped NNSS create a photocathode design based on indium gallium nitride/aluminum nitride (InGaN/AlN) heterostructures.

*Publications: Buckles, R., Crawford, K., Sun, K.-X. & O'Gara, P. Next-Generation Photomultiplier Detectors Using Transmissive III-Nitride Semiconductor Electrodes. in Nevada National Security Site, Site-Directed Research and Development: Fiscal Year 2016 Annual Report, 59–68 (2017).*

*Buckles, R. & Sun, K.-X. Next-Generation Photomultiplier Detectors Using Transmissive III-Nitride Semiconductor Electrodes in Nevada National Security Site, Site-Directed Research and Development: Fiscal Year 2017 Annual Report, 61–67 (2018).*




Micrographs of an InGaN photocathode device with progressively higher magnification. Units are microns. **(A).** 1 mm device showing circular mesa structure and surrounding plane. Top contact ring is 100 µm wide. **(B).** Circled areas of interest: edge and plateau. **(C).** Mesa edge. Bright white stripes show the silicon dioxide ($SiO_2$) edge passivation covering the mesa edge. The darkest band is the mesa edge with its bottom toward left and plateau toward right. The brightest regions are bare gold contacts. **(D).** The honeycomb metallized plateau is a 5 µm wide strip of gold suspended on $SiO_2$ passivation. This plateau acts as a control "grid" for enhancing the under-surface field for emission without allowing strong conduction to grid. This is very much an optical planar triode, given a collector anode.

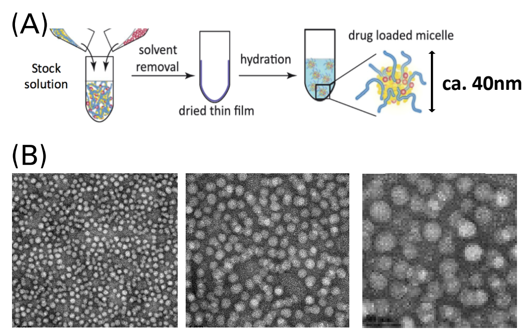
## Hyperloaded poly(2-oxazoline) micelles as personalized drug carriers for brain tumors



*Graduate Student: **Duhyeong Hwang***
*PIs: **Alexander V. Kabanov and Marina Sokolsky***
*Eshelman School of Pharmacy, University of North Carolina-Chapel Hill*

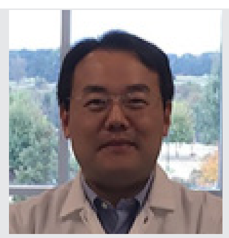
Work from the Kabanov group at UNC Eshelman School of Pharmacy focuses on polymeric micelles based on amphiphilic poly(2-oxazoline) block copolymers with unprecedented high capacity for poorly soluble uncharged drugs and drug combinations. In this work, a novel polymeric micelle formulation of vismdegib (POx-vismo) was used to load the poorly soluable drug into the amphiphilic poly(2-oxazoline) copolymer. Using the thin film method, a mixture of the drug and polymer was hydrated with aqueous mediums to spontaneously form nano-sized polymeric micelles. The advantageous properties include high loading capacity of the drug, sustained-release of cargo, optimal nanoparticle size distribution, and enhanced stability and exposure of the drug.

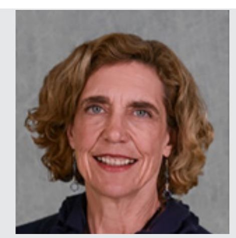
*Publication: Hwang, D. et al. Hyperloaded poly(2-oxazoline) micelles as personalized drug carriers for brain tumors. Neuro-Oncology, 21 (2019).*




**(A).** Illustration depicts Pox-vismo micelle formulation. **(B).** TEM micrograph of POx-vismo. (Scale: 200 nm (left), 100 nm (middle), 50 nm (right).

## Dually-targeted platelet-inspired nanocell shows promise for healing a broken heart

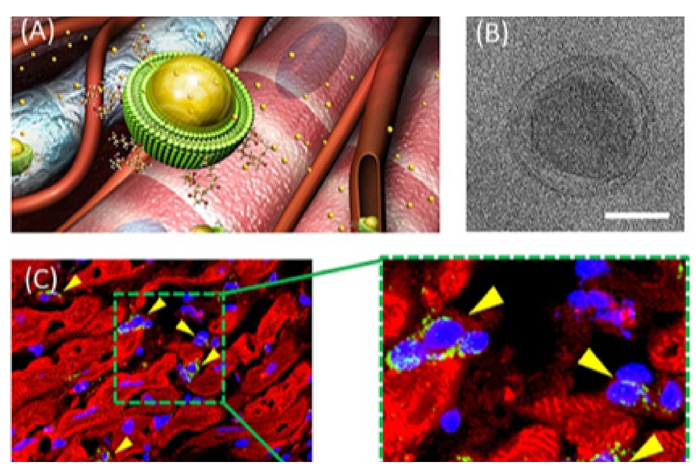




*Postdoc: **Teng Su** | PIs: **Ke Cheng and Frances S. Ligler***
*Joint Department of Biomedical Engineering, University of North Carolina-Chapel Hill and NC State University*
*Department of Molecular Biomedical Sciences, NC State University*

Cardiovascular disease is the leading cause of mortality in the world. Stem cell therapy is promising for heart regeneration but suffers from several limitations including low cellular retention and non-targetability. To overcome these challenges, the Cheng lab developed a platelet-inspired nanocell (PINC) that has a cardiac stromal cell (CSC) core and a platelet membrane shell. The CSC core consists of therapeutic CSC-secreted factors encapsulated in an FDA-approved biodegradable poly (lactic-co-glycolic acid) nanoparticle. The platelet membrane is decorated with prostaglandin E2 (PGE2) to enhance targeting to both the damaged blood vessels and heart muscle cells after ischemic injury and facilitate the endogenous repair of damaged heart tissue through PGE2/EP receptor signaling. In a mouse model of heart attack, PINC therapy promoted the growth of cardiac cells and vasculature and activated endogenous stem/progenitor cells, which contributed to the restoration of the heart's pumping function.

*Publication: Su, T. et al. Platelet-Inspired Nanocells for Targeted Heart Repair After Ischemia/Reperfusion Injury. Adv. Funct. Mater., 29 (2019) (Cover Feature).*



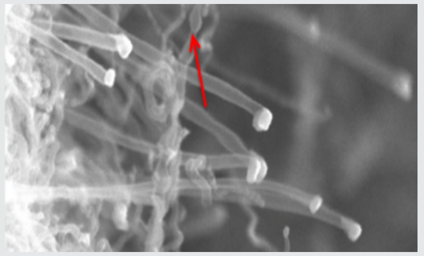

**(A).** Schematic illustration. **(B).** Transmission electron micrograph showing the structure of PINC. **(C).** Visualization through confocal laser scanning microscopy of AURKB, a specific marker of cytokinesis, in cardiomyocytes in the peri-infarct regions of PINC-recipient mouse hearts 4 weeks post-treatment. Scale bars, 100 nm (B); 20 μm (C).

## Melamine as a single source for fabrication of mesoscopic 3D composites of N-doped carbon nanotubes on graphene



*Student: **Xiao-Ling Yan[1]** | PIs: **Gui-Ping Dai[1,2] and K. Vinodgopal[2]***
*1. School of Resources Environmental & Chemical Engineering, Nanchang University, Nanchang, China. 2. Department of Chemistry and Biochemistry, North Carolina Central University*

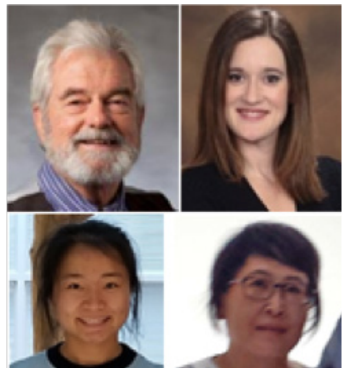
Integration of two-dimensional graphene and one-dimensional carbon nanotubes (CNTs) to create potentially useful 3D mesoscopic carbon structures with enhanced properties relative to the original materials is very desirable. Here simple chemical vapor deposition (CVD) methods were used to fabricate bead-like nitrogen-doped CNT/graphene composites (NCNT/G) via a simple pyrolysis of the N-rich melamine in the presence of graphene oxide (GO) as a substrate using a Mn–Ni–Co ternary catalyst. These bead-like N-doped CNTs (red arrow in figure) are vertically organized on the GO nanoplates yielding a 3D structure. These structures have been characterized by field-emission scanning electron microscopy, transmission electron microscopy, X-ray diffraction, Raman spectroscopy, isothermal analyses, and X-ray photoelectron spectroscopy. The three dimensional NCNT/G hybrids have unique network structures, moderate graphitization, high specific surface area, good mesoporosity, and N doping, which makes them promising materials for energy applications.



SEM image of NCNT-G (the red arrow refers to the bead-like NCNT).

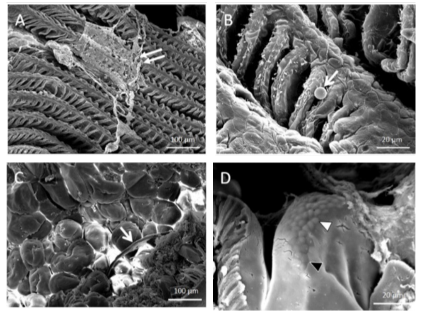
*Publication: Yan, X-L. et al, Melamine as a single source for fabrication of mesoscopic 3D composites of N-doped carbon nanotubes on graphene. RSC Adv, 8 (2018).*

## Pathways of concern for chronic microplastics exposure in adult fish



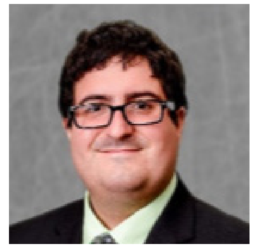
*Staff and visiting scholars: **Melissa Chernick[1], Lingling Hu[1,2], Mei Zhu[1,3]** PI: **David E. Hinton[1]** 1. Nicholas School of the Environment, Duke University 2. Inner Mongolia University of Finance and Economics, Hohhot, China 3. State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, China*

Environmental accumulation and organismal exposures to various types, sizes, and shapes of plastics increases as its production grows. However, little is known about uptake and response in organisms. Adult medaka, a laboratory model fish, were exposed to either synthetic microfibers or spherical microplastics. SEM localized these microplastics to gills and digestive tract. Microfibers caused surficial erosions of gill arches and filaments as well as fusion of lamellae and increased mucus production in the form of strands or sheets. Similar mucus production was seen on gills with exposure to spherical microplastics, indicating an acute response to these irritants. Additionally, gut responses were in the form of swollen enterocytes and eroded brush borders on apices of folds. The use of SEM revealed responses not visible with other methods (e.g., histology) and illustrated primary pathways of concern and damage in these fish, leading to a better understanding of environmental and host processes.



**(A-D).** SEM images of gills **(A-B)** and gut **(C-D)** of medaka exposed to microfibers or microplastics showing **A)** mucous sheets in response to polypropylene microfiber exposure (double arrow), **B)** spherical polystyrene microplastic between secondary lamellae (arrow), **C)** polyester microfiber caught in folds of foregut (arrow), and **D)** swollen enterocytes (white arrowhead) and erosion of brush border (black arrowhead) on apex of gut fold.

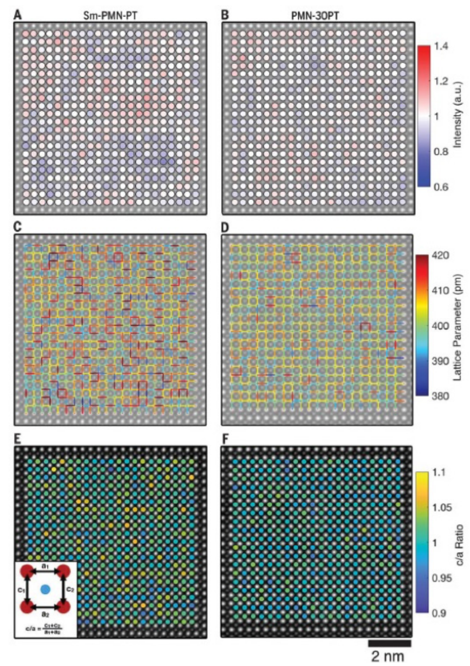
## Giant piezoelectricity of Sm-doped $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ single crystals




*Post-doc: **Matt Cabral** | PI: **Jim LeBeau***
*Department of Materials Science and Engineering, NC State University*

High-performance piezoelectrics benefit transducers and sensors in a variety of electromechanical applications. The materials with the highest piezoelectric charge coefficients (d33) are relaxor-$PbTiO_3$ crystals, which were discovered two decades ago. Progress toward improving piezoelectric responses in devices has been slow. In this work, a new process was employed to grow Sm-doped $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (Sm-doped PMN-PT) single crystals. The resulting crystals had high piezoelectric coefficients (3400 to 4100 picocoulombs per newton, double that of undoped PMN-PT) and exhibited good property uniformity. By examining the crystals at the atomic scale using scanning transmission electron microscopy, researchers determined that the piezoelectric properties arise from the local structural heterogeneity introduced by $Sm^{3+}$ dopants. This strategy enlarges the usable portion of the as-grown crystals and in turn improves reliability for piezoelectric devices requiring large crystal wafers with minimal variation in properties, providing commercialization opportunities for high-performance piezoelectric applications.

*Publication: Li, F. et al. Giant piezoelectricity of Sm-doped $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ single crystals. Science, 364 (2019).*



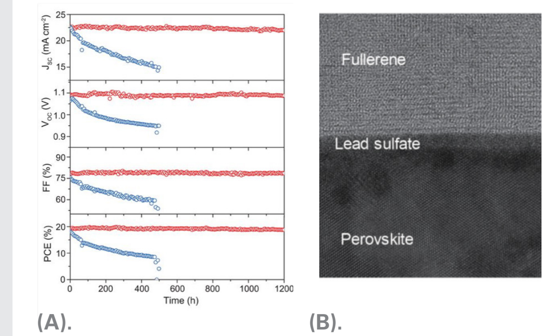

Atomic-resolution HAADF-STEM images for Sm-doped PMN-PT and PMN-30PT crystals recorded along the [010] crystallographic direction.

## Stabilizing halide perovskite surfaces for solar cell operation with wide-bandgap lead oxysalts


*Post-doc: **Shangshang Chen***
*PI: **Jinsong Huang** Department of Applied Physical Sciences, UNC-Chapel Hill*

Perovskite solar cells typically face long-term instability issues under realistic operation conditions, which remains a critical hurdle to overcome before their commercialization. This work shows that converting the surfaces of lead halide perovskite to water-insoluble lead (II) oxysalt through reaction with sulfate or phosphate ions can effectively stabilize the perovskite surface and bulk material. These capping lead oxysalt thin layers enhance the water resistance of the perovskite films by forming strong chemical bonds. The wide-bandgap lead oxysalt layers also reduce the defect density on the perovskite surfaces by passivating undercoordinated surface lead centers, which are defect-nucleating sites. Formation of the lead oxysalt layer increases the carrier recombination lifetime and boosts the efficiency of the solar cells to 21.1 percent. Encapsulated devices stabilized by the lead oxysalt layers maintain 96.8 percent of their initial efficiency after operation at maximum power point under simulated air mass (AM) 1.5 G irradiation for 1200 hours at 65°C, which is one of the best device stabilities tested under operation conditions.

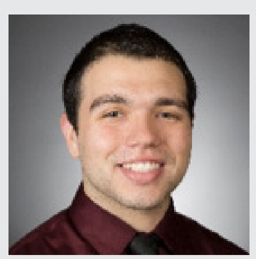
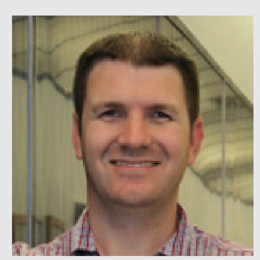
*Publication: Yang, S. et al. Stabilizing halide perovskite surfaces for solar cell operation with wide-bandgap lead oxysalts. Science, 365 (2019).*




**(A).** Stability test of encapsulated solar cell devices based on control (blue) and sulfate-treated (red) perovskite active layers control **(B).** Cross-section HR-TEM image of perovskite device sulfate-treated

**Dr. Jinsong Huang and his group** received the 2019 RTNN Collaborative Research Award for their work highlighted here. The Collaborative Research Award recognizes users who are working with colleagues across at least two of the three institutions and utilizing RTNN facilities.

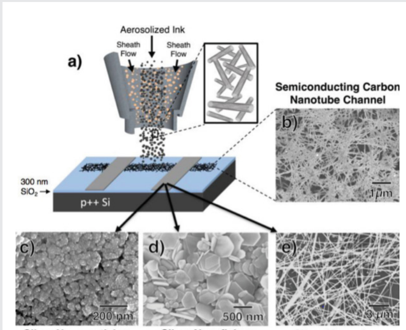
## Impact of Morphology on Printed Contact Performance in Carbon Nanotube Thin-Film Transistors

*Graduate Student **Jorge Cardenas***
*PI: **Aaron Franklin***
*Department of Electrical and Computer Engineering, Duke University*

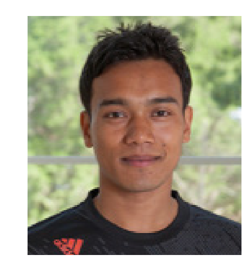
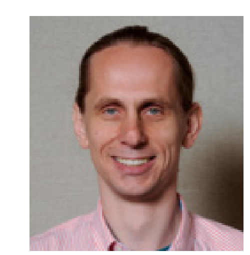
Silver nanoparticles are a widely used conductive material in printed electronics due to high conductivity and low cost. However, the interface of silver with carbon nanotubes in thin film transistors is often suboptimal. In this work, three distinct silver morphologies were compared including nanoparticles, nanoflakes, and nanowires. Nanoflake inks yielded the best electrical performance but with tradeoffs of print resolution and process temperature

*Publication: Cardenas, J. et al. Impact of Morphology on Printed Contact Performance in Carbon Nanotube Thin-Film Transistors. Adv Funct Mater, 29 (2019).*



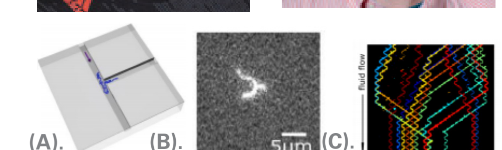

The silver contact morphologies explored in the work. **a)** Illustration of the deposition process and printed carbon nanotube-thin film transistor (CNT-TFT) structure. **b)** SEM image of the randomly oriented CNT network serving as the TFT channel. **c–e)** SEM images of the silver contact morphologies

## Nanoplumbing with 2D materials

*Graduate Student: **Saroj Dangi***
*PI: **Robert Riehn***
*Department of Physics, NC State University*

Nanofluidic devices with cross-sections around 100x100 $nm^2$ and many microns are used for genetic mapping applications and the interrogation of DNA-protein interactions. They can also enable the targeted manipulation of the DNA conformation. Here a distributed network of channel junctions enables complex manipulations of DNA that are dependent on flow speeds such that molecules travel along intersecting, but quasi-ballistic paths. DNA and liquid do not travel along the same directions through the device; this may enable on-chip preparation and modification of DNA as it allows for buffer exchange.




**(A).** A junction of two nanochannels induces folded configurations of DNA. **(B).** A fluorescence micrograph of a DNA molecule at a nanochannel junction. **(C).** Overlaid collection of multiple DNA molecules through large-area device of such junctions.

*Publication: Dangi, S. and Riehn, R. Nanoplumbing with 2D Metamaterials. Small, 15 (2019).*




# BUILDING THE USER BASE

The overarching goal of the RTNN is to build the user base. We have identified three barriers to engaging new users:

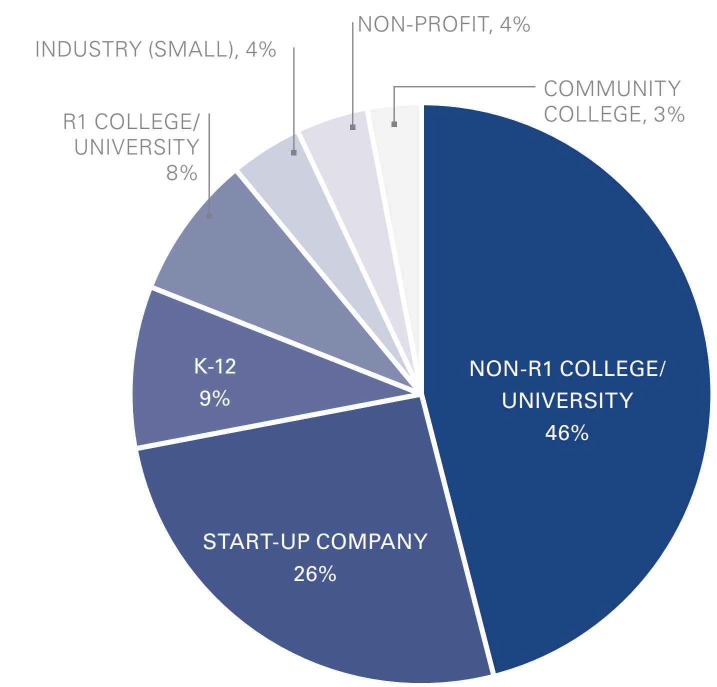
- **Knowledge** of the existence of the facilities and how to access them;
- **Distance** to travel to the facilities;
- **Cost** of accessing the facilities.

To address these barriers, we have implemented targeted, innovative new programs and activities and strengthened existing ones to attract and retain new and current users.

### RTNN Kickstarter Program

This program supports initial use of RTNN nanotechnology facilities by new, non-traditional users by providing **free access to facilities** for work valued at up to $1,000. Proposed projects must be focused on research, preliminary development activity, or educational programming in an area of nano-scale science, engineering, and/or technology. 70 projects have been selected for the Kickstarter program, receiving over 1,200 hours in facility use. The majority of participants hail from non-R1 colleges/universities, start-ups, and K-12 classrooms. **44 percent of participants in this program have continued to use facilities with their own financial support leading to an additional $125,000 in revenue to the facilities**. In addition, several participants have indicated that they are using the data from their projects to support research proposals and include RTNN facility usage in the proposed work.

KICKSTARTER PARTICIPANTS




### Nanotechnology, A Maker's Course

RTNN developed a free online course to give an overview of nanotechnology tools and techniques and demonstrate equipment within RTNN facilities. The goal of the course is to introduce nanotechnology concepts to students and give them a better sense of the various tools' capabilities. The course includes eight modules, each focused on a different fabrication or characterization concept. Students first learn the science behind a specific technique or instrument. The lectures make the information accessible to a large audience, using simple language and relatable analogies to everyday things. In-lab demonstrations of the equipment follow each lecture with an explanation of each step in the process. **Since the course launched in September 2017, >75,000 people have visited the course site and >15,000 have enrolled in the course**. The course has attracted learners from more than 155 countries across the world garnering scores of positive reviews.
***coursera.org/learn/nanotechnology***

RTNN staff member Michelle Plue demonstrates mucro-CT sample preporation in *Nanotechnology, A Maker's Course*.

# K-GRAY ENGAGEMENT

- **>3,500 people reached in Year 4**
- **>60% participation by underrepresented groups in STEM**

### Girls STEM Day

In May, 140 Girl Scouts and their families traveled to Duke University to learn from and work with women in STEM careers across the Triangle (volunteers from 43 companies/institutions). Girl Scouts earned badges in DNA, robotics/AI, and chemistry of cosmetics through a variety of different activities including use of a scanning electron microscope. The event includes parent-focused activities (e.g. financial sessions) to support girls success in STEM fields.

Girls work in teams to explore robotics/AI during Girls STEM Day at Duke.

### Visits to RTNN Facilities

In 2019, over **1,700 K-12 students** visited the facilities to learn the size of a nanometer, discover real-world nanotechnology applications, see the equipment in action, and participate in fun hands-on activities.

### Visits to Classrooms

RTNN staff also traveled to many K-12 classrooms and schools to introduce nanotechnology, interacting with over **300 students**. These visits are paired with hands-on activities to engage students. We often travel with a portable, desktop SEM making it possible for us to take our facilities to the classroom. The desktop SEM is user-friendly and approachable. Students can begin using it right away without complex and lengthy training sessions.

Middle school students examine samples with light microscopes and note their observations.

### Science Celebrations

Each year, North Carolina reserves the month of April for the North Carolina Science Festival. The NC Science Festival includes events across the state at K-12 schools, museums, universities, parks, etc. In 2019, RTNN sponsored NanoDays, which takes place annually at NC State. We offered lab tours and conducted nanotechnology demonstrations. At this event, RTNN staff introduced the facilities, demonstrated different techniques, and provided hands-on activities. There are also several STEM/STEAM fairs and expos at local schools during the NC Science Festival. We took part in a number of these events by hosting RTNN **booths for >1,500 visitors** with hands-on activities related to nanotechnology.

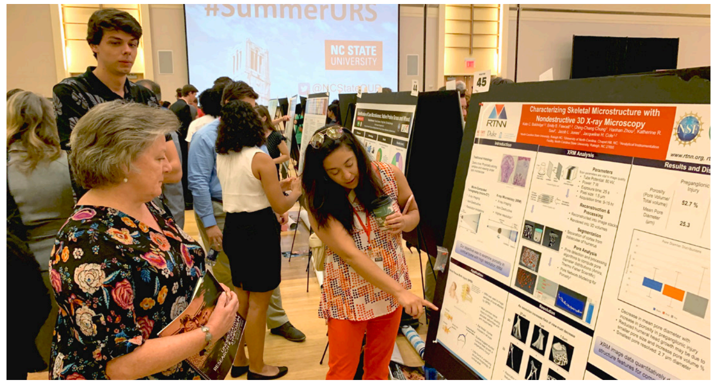
RTNN Ambassadors help visitors with a photolithography activity during the NC Science Festival at the Chapel Hill Public Library.

### Community College Engagement

The RTNN held its fourth two-day nanotechnology workshop for community college and small college educators in August 2019. Participants operated multiple tools in the clean room to fabricate a working LED device and spent time incorporating nanotechnology instruments and techniques into their community college curricula. RTNN staff members also worked with Durham Technical Community College faculty members to incorporate the scanning electron microscope (SEM) into engineering, physics, and biology coursework. This included both a lecture and hands-on component with the portable SEM.

Two Durham Tech students also conducted research in RTNN facilities during the summer and presented their work at the NNCI REU Convocation hosted by Cornell University. Katie Baldridge worked with Dr. Jacque Cole to develop procedures for the X-ray microscope's new analytical software through the study of bone impacted by brachial plexus injury. Caleb Christie used Raman spectroscopy to characterize different nanoparticles' ability to bind to phosphorus under the guidance of Dr. Jacob Jones.

Community college educators gowned up in the clean room.



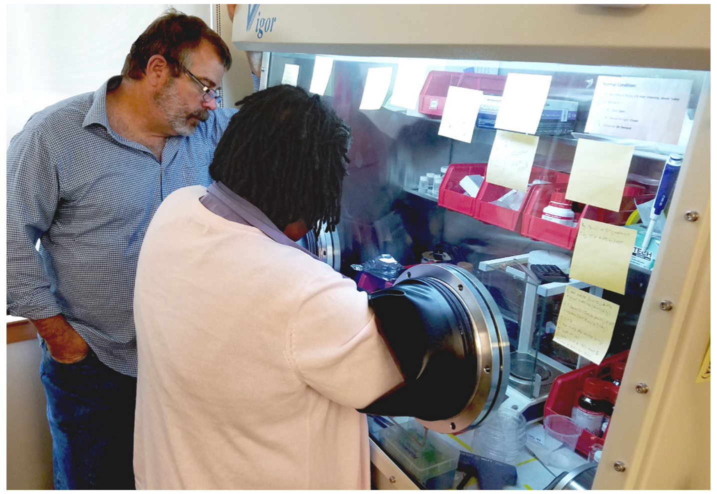
REU Student Katie Baldridge presents her work at NC State's Summer Undergraduate Research Symposium.

### Remote Use of Facilities

To overcome distance as a barrier to access, users can access nano-facilities remotely with the assistance and expertise of RTNN students and staff. Fabrication and/or characterization are performed on-site and streamed live to the remote user. RTNN staff and students are available to explain the procedures, discuss technical aspects of the equipment, and answer questions throughout the process.

### Research Experience for Teachers (RET)

Eleven teachers participated in the Atomic Scale Design and Engineering RET Program. Educators worked in small teams at engineering labs at NC State, Duke, or UNC-Chapel Hill or in industry. Projects were selected to expose educators to a variety of nanotechnology fabrication and characterization tools. Educators created lesson plans to implement into their classroom with one lesson plan focused on a specific tool.



RET participants Mark McLean and Linda Lanier work in a glove box in Dr. Jim Cahoon's lab.

### Technical Workshops and Short Courses

The RTNN hosts training and technical workshops at member institutions. These workshops are provided at low cost to internal and external users. They provide technical and/or educational training on nano-fabrication and/or characterization equipment and techniques. In 2019, RTNN held 22 workshops and short courses with over 175 participants.

Attendees listen to a presentation by Dr. Greg Parsons at an RTNN workshop focused on atomic layer deposition.

### RTNN Student Ambassadors Program

The RTNN Student Ambassadors Program was established this year to engage students in the RTNN's mission to bring nanotechnology tools and expertise to new researchers and the public. Ambassadors represent the RTNN to visitors and program participants, increase awareness of the RTNN, and extend outreach activities. RTNN ambassadors traveled to schools and museums, guided tours, and sparked enthusiasm about nanotechnology.

RTNN Student Ambassador Alex Hsain advises a student in SEM imaging during a STEM RTP event.

## Student Outreach Awards

This award recognizes students who have dedicated their time to support RTNN education, outreach, and engagement activities. This award shows our appreciation to the energy that these students have devoted to bringing in a future generation of users. RTNN Student Ambassadors **Abby Carbone** (NC State), **Jeromy Rech** (UNC), and **Rachel Cohn** (Duke) were the 2019 recipients of this award.

Abby Carbone

Jeromy Rech

Rachel Cohn

# NANOTECHNOLOGY LEADERSHIP IN THE TRIANGLE

The RTNN engages with the community to promote nanotechnology in the Triangle. We work with community college educators and other local educators to help them incorporate nanotechnology concepts and equipment into the classroom. We have partnered with Morehead Planetarium and Science Center to distribute nanotechnology educational activities to K-12 schools across the state. We are engaged with 4H and the North Carolina Girl Scouts to strengthen our ability to reach the remote parts of our state.

The RTNN connects researchers on emerging scientific topics at the forefront of nanotechnology. In addition, we actively seek out opportunities to strengthen and broaden our capabilities including proposals for: Research Experience for Undergraduates and Major Research Instrumentation at all three institutions. The RTNN RET Program resulted from one of these efforts.

We have also organized multiple events at the Chapel Hill Public Library and the Museum of Life and Science. These events are widely publicized by the library/museum but also provide a means to reach populations who may be patronizing the venue for other reasons. At these events, we bring the portable SEM and other hands-on activities to attract visitors.

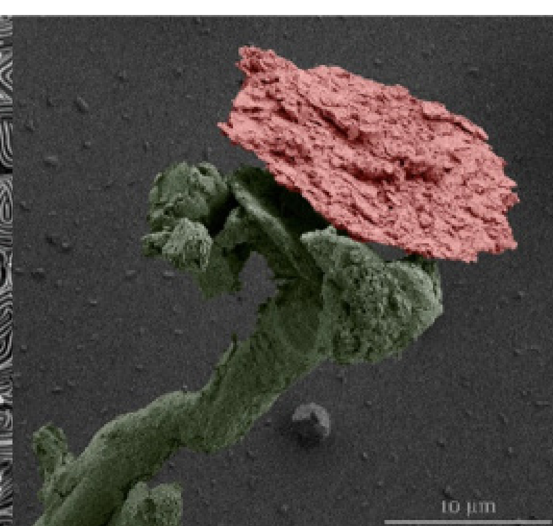
In honor of National Nanotechnology Day on October 9th, the RTNN hosted teachers through STEM RTP's ExternTrip program. Teachers had the opportunity to gown up and tour the clean room as well as spend time analyzing samples

RTNN Student Ambassador Abby Carbone gets some SEM imaging help from a museum visitor.

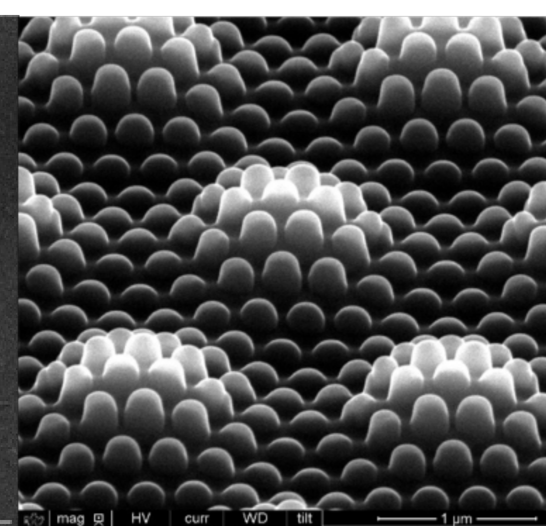
using the scanning electron microscope. Leading up to this event, the RTNN hosted an image contest, *There's Plenty of Beauty at the Bottom*. The winning images represented work conducted at our facilities and are featured below.

Each fall, the RTNN helps to organize the Carolina Science Symposium. This student-focused conference gives early career students their first opportunity to present their work in a professional setting. Attendees practice and perfect their presentation skills, network with their peers, and learn about the facilities and tools available within the RTNN. Over 125 attendees from across the Southeast participated this year, and attendance continues to grow each year.

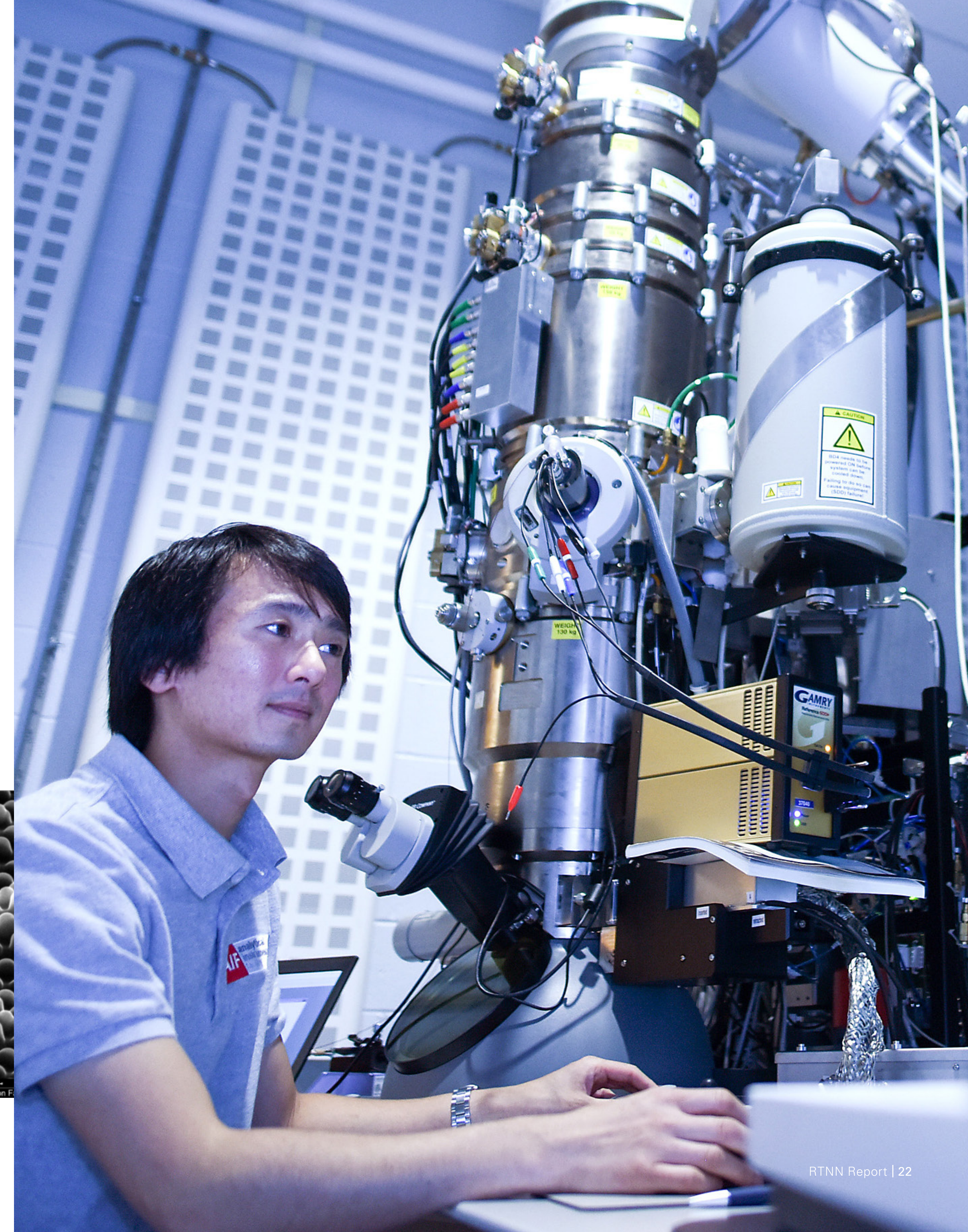
Melissa Chernick




Michael Valerino




Nichole Miller



# NATIONAL IMPACT AND ENGAGEMENT

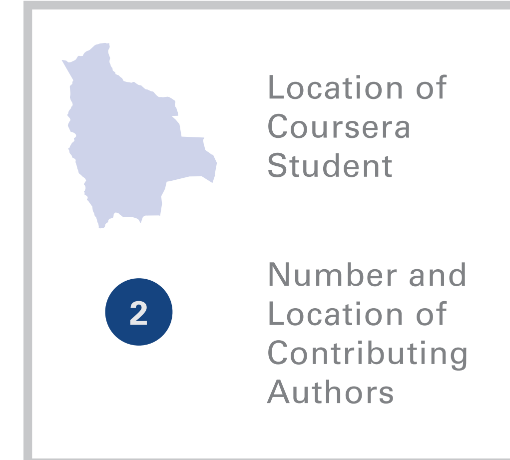
The RTNN is actively involved in NNCI working groups and committees

- Leadership of diversity subcommittee
- Membership in K-12 education and outreach. workforce training, online learning, environmental health and safety, EBL, and XPS working groups

SMIF staff member Holly Leddy received the NNCI Education and Outreach Award for the vital role she plays in planning and implementing the RTNN's education and outreach programs.

Our staff attend diverse national events and conferences, including education and research-focused conferences, to raise awareness of RTNN and NNCI's educational and technical programs. In April, we debuted a new video at the MRS meeting in Phoenix to raise awareness of RTNN and NNCI capabilities.

The RTNN is also growing internationally. *Nanotechnology: A Maker's Course* draws learners from around the world, and some of these learners have begun to use RTNN programs and facilities. In addition, many publications acknowledging RTNN facilities have international authors. (*Note: authors listed on multiple publications are counted for each publication).*




# GLOBAL REACH

# NANOTECHNOLOGY OUTCOMES

## OUTCOME NUMBERS

**$84.1 M** in research activity, as defined by annual research expenditures, for projects that utilized the facilities

**22** Patents awarded

**24** Invention disclosures

**158** Patents filed

**92** Graduate Degrees earned

**RTNN user satisfaction and programming are assessed regularly by Dr. David Berube's team within PCOST (Public Communication of Science and Technology).**

### Kickstarter program feedback

To assess the Kickstarter program, semi-structured interviews have been conducted with 18 participants. The feedback from participants in the Kickstarter program was overwhelmingly positive. Respondents were happy with the overall program and indicated they will return to the facilities. **A common theme from respondents was gratitude for RTNN staff**. Many staff members were thanked by name by the program participants.

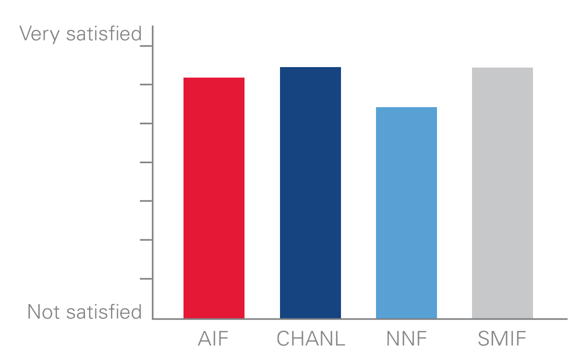
> **"...everything just went 1-2-3 and it was truly perfect. And in fact, helped our research project move -- you'd have to put logarithmic; it really helped us move along in our research project."**

### Nanotechnology, A Maker's Course

After completing the course, students receive a survey through the Coursera platform. Overall, students are very satisfied with the course. **90 percent of respondents** noted that they were *likely* or *very likely* to recommend the course to others. **78 percent of respondents** noted that they had a better knowledge of the capabilities of RTNN.

### User assessment: satisfaction

All users received an online survey to obtain demographic and satisfaction data. Overall, facility users were very satisfied in the facility they used, and facility satisfaction was consistent between RTNN's four core facilities. **Greater than 98 percent of users indicated that they would return to the lab if further work was necessary.**




### Future research direction

Moving forward we will continue to evaluate our users' satisfaction to better understand how users experience the facilities. We will aim to answer questions like: How do individuals from different backgrounds, experiences, disciplines, and demographics experience our facility differently? and How do we make laboratories more usable and increase satisfaction? This results of this work will influence staffing, leadership, process, and tool acquisition decisions.



# GETTING STARTED WITH RTNN

### Connect with Experts For:

- Training to independently operate equipment
- Fabrication and analytical services
- Consultation, collaboration, and support for process and instrumentation development
- Interactive educational opportunities for students
- Continuing education programming in nanotechnology

### Contact Us

| | |
|---|---|
| Drop us a line | **rtnanonetwork@ncsu.edu** |
| Give us a call | **919.515.6171** |
| Visit us online | **rtnn.org** |
| Sign up for our newsletter | **rtnn.ncsu.edu/contact-us** |

### Follow Us on Social Media

linkedin.com/company/research-triangle-nanotechnology-network

@RTNNSocial

facebook.com/RTNNSocial

### Reach Out to our Directors

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**Jim Cahoon**
UNC-CH Site Director, jfcahoon@unc.edu

**David Berube**
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This report is based in part upon work supported by the National Science Foundation (NSF) under Grant No. ECCS-1542015. Any opinions, findings and conclusions or recommendations expressed in this report are those of the authors(s) and do not necessarily reflect the views of the NSF.