RESEARCH TRIANGLE NANOTECHNOLOGY NETWORK

2018 REPORT


NC STATE UNIVERSITY

NSF

Duke UNIVERSITY

National Nanotechnology Coordinated Infrastructure

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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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 sixteen 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 nine nano-fabrication and characterization facilities and over 100 principal faculty 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.

2018 Program Highlights

RTNN 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. Highlights from the past year include:

- More than **1,300 unique annual users** accessed RTNN facilities for **over 55,000 hours** of experimental time, an increase of 8% from the previous year
- **More than 4,900 K-12 participants** were reached with **1,100 engaged in hands-on programs** in the facilities
- ***Nanotechnology: A Maker's Course***, a Coursera online course, enrolled more than 6,500 learners in >130 countries
- **The Kickstarter program** provided ~200 hours on nanotech tools to 12 non-traditional and new users
- RTNN visited regional K-12 classrooms to give more than 1,100 students training and hands-on experiences like operating a **portable scanning electron microscope (SEM)**
- **Community college faculty** worked in a cleanroom to fabricate an LED device and developed curricula founded in nanotechnology concepts at RTNN's annual educator workshop
- **27 technical workshops and short courses** exposed over 140 participants to new nanotechnology tools and ideas and brought them together to spark new collaborative work

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.

Analytical Instrumentation Facility (AIF) provides nano-characterization of both hard and soft materials and has over 8 in situ stages (liquid cells, heating, mechanical loading, electrical biasing) for microscopy and diffraction.

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.

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.

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

BY THE NUMBERS

- **3** major research universities
- **9** shared 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 **50,000** annual hours of collective use

AFFILIATED FACILITIES

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.

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

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.

Center for the Environmental Implications of Nanotechnology (CEINT) has multiple instrumented environmental mesocosms in the Duke Forest to evaluate the effects of nanomaterials on simulated freshwater wetlands. Nanoparticle transport tracking and interaction with environmental media is accomplished through hyperspectral imaging, near IR fluorescence, static light scattering, variable angle dynamic light scattering, and continuous image analysis.

Zeis Textile Extension Education for Economic Development Center (ZTE) provides professional education and services including hands-on training for all aspects of textile processing including process development and evaluation, analytical services, pilot production, and physical property testing of fibers, yarns, and fabrics. Within ZTE, The Textile and Forensic Analytical Laboratory offers comprehensive chemical analysis of nanofibers, dyes, and other associated chemistries.

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 include:

- Hot embosser
- Electrospinning of nanofibers
- High temperature furnaces for SiC
- Positron annihilation spectroscopy
- Small-angle X-ray scattering (SAXS)
- Extreme-resolution scanning electron microscopy (SEM)
- In situ heating and liquid cell transmission EM (TEM)
- Chemically-sensitive, atomic-resolution scanning TEM (STEM)
- Cryo-TEMs for biological and soft materials imaging and molecular structure determination
- High-Resolution NMR spectroscopy
- Simulated wetland and atmospheric ecosystems for environmental studies

NEW TOOLS AND CAPABILITIES

FEI Titan Krios TEM

The Thermo-Fisher/FEI Krios 300kV Cryo-Transmission Electron Microscope (TEM) enables users to examine biological samples at the molecular level. It is equipped with an auto-loader that can hold up to 12 samples and automated image acquisition software. This instrument is capable of single particle analysis and 3D tomography.

The FEI Talos TEM is equipped with a complement of in situ sample holders to explore materials as a function of temperature, atmosphere (liquid or gas), and electrical biasing; a high speed camera to capture detailed structural changes during in situ experiments; cryogenic sample preparation and holders to image beam sensitive materials; electron energy loss spectroscopy (EELS) and energy dispersive X-ray spectroscopy (EDS) to correlate nanoscale structure and chemistry; and tilt-tomography to measure three dimensional (3D) structural details.

Rigaku Smart Lab XRD

The Rigaku SmartLab X-ray Diffractometer (XRD) is capable of looking at powders and thin films. In addition to traditional XRD experiments, it is also capable of in-plane diffraction and small angle X-ray scattering (SAXS), and there are options for working with samples in inert environments and at various temperatures.

The Asylum Cypher ES Environmental Atomic Force Microscope (AFM) allows for temperature control and fluid or gas perfusion. It also has blueDrive photothermal excitation, which, by directly exciting the cantilever photothermally, provides significant ease of use and performance benefits for imaging topography, mechanical, electrical, and magnetic properties in air and liquids.

The YES HMDS/image Reversal Oven is able to process pieces up to full cassette batches of 4” and 6” wafers. This tool allows users to vapor-prime substrates with hexamethyldisilazane (HMDS) for far superior resist adhesion than the current liquid-phase spin-on method. The image reversal function uses NH_3 to reverse any positive photoresist. This method also reverses sidewall profile for liftoff and allows users to work with more repeatable positive resists.

The Bruker Hysitron TI 980 Nanomechanical Test System

The Bruker Hysitron TI 980 Nanomechanical and Nanotribological Test System includes nanoscratch, nanowear, high resolution in situ scanning probe microscopy imaging, quantitative nanoscale-to-microscale indentation, dynamic nanoindentation, and high speed mechanical property mapping

The Keyence VK-X1100 3D Laser Scanning Confocal Microscope is a non-contact 3D metrology system that performs nanometer level profile, roughness, and thickness measurements on nearly any material.

3D printed piece (grey) custom made with the printer to hold a magnet and allow a viewport

The FormLabs Form 2 Desktop Stereolithography (SLA) 3D Printer can print objects as large as 15 cm tall with feature sizes as small as 140 µm and layer thicknesses of as little as 25 µm. The printer can produce high quality 3D models of data taken directly from micro-CT systems. To date the printer has been used to create high-quality replicas of one-of-a-kind scanned objects (e.g., fossils and historical artifacts), teaching tools for tour groups, and custom parts for research labs on campus.

Leica EM TIC 3x Ion Beam Milling System allows production of cross-sections and planed surfaces for SEM, microstructure analysis [EDS, wavelength-dispersive spectroscopy (WDS), Auger, electron backscatter diffraction (EBSD)], and AFM investigations. Its cooling stage allows for the milling of temperature sensitive samples without melting.

The Symmetry EBSD Detector was added to the FEI Verios SEM, providing superior orientation microscopy capabilities. Data can be collected at speeds up to 3,200 pixels/second, even at reduced operating voltages and beam currents, allowing data collection on poorly conducting specimens.

The SVG Series 90S Coat, Bake, and Chill Track System has been upgraded to allow 100 mm and 150 mm multiwafer processing. It has the capability of coating substrates with an automated dispense system or manual dispensing for low volume work. Vacuum bake hot plates provide precise and uniform baking. Chill plates provide temperature stabilization for post bake or pre-coating. Processes can be stored for later use and easily updated through the console.

Heidelberg Instruments µPG 101 Direct Write System

The Heidelberg Instruments µPG 101 has the ability to write high precision photo masks in-house with immediate turnaround at very low cost. This capability allows for the fabrication of 5” reticles for the 5X reduction stepper, which can then resolve features down to 0.6 µm.

The Titan Aberration-corrected Scanning Transmission Electron Microscope was upgraded to a 64-bit operating system and hardware. A 4D STEM direct electron detector was also added. It captures 1000 diffraction patterns/second to enable formation of STEM images in post processing. It can detect from one to a million primary electrons per pixel (1,000 times current dynamic range) at 100 times the speed of conventional detectors.

The Thermo-Fisher/FEI Apreo SEM is outfitted with both electrostatic and magnetic immersion technology, an in-lens backscatter detector, beam blanker for use with e-beam lithography, and an EDS detector.

The Suss Delta 12L Solvent/Developer Spray Tool is designed for wet processing of wafers up to 300 mm. Wafer cleaning, puddle/spray development, lift-off, and resist stripping are a few examples of the processes enabled by this tool.

The Bruker Hyperion FTIR Microscope is capable of transmission and attenuated total reflectance (ATR) measurements from 600 to 7,500 cm^{-1} with 1 cm^{-1} spectral resolution. It can map spectra with a lateral resolution ranging from 20 to 250 µm.

Bruker SkyScan 1174 Micro-CT

A Bruker SkyScan 1174 Micro-CT System was purchased for use in outreach activities. It is used in conjunction with the micro-CT immersive lab experience that was developed last year.

Multilayer Polymer Film Identification using Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS): Multilayer laminate films consist of both polymeric and inorganic layers. These films are used in a variety of industries such as adhesives, coatings, and packaging materials. To date, there are very few analytical techniques to identify the chemical composition, defects, and inclusions on polymer films without extraction. RTNN staff have developed the use of ToF-SIMS for multiple layer film cross section analysis which provides rich chemistry information on both polymeric and inorganic layers with sub-micron resolution. SIMS spectra are first obtained with a low energy electron beam. The characteristic peaks are then imaged to identify and determine the spatial distribution of polymer and inorganic layers.

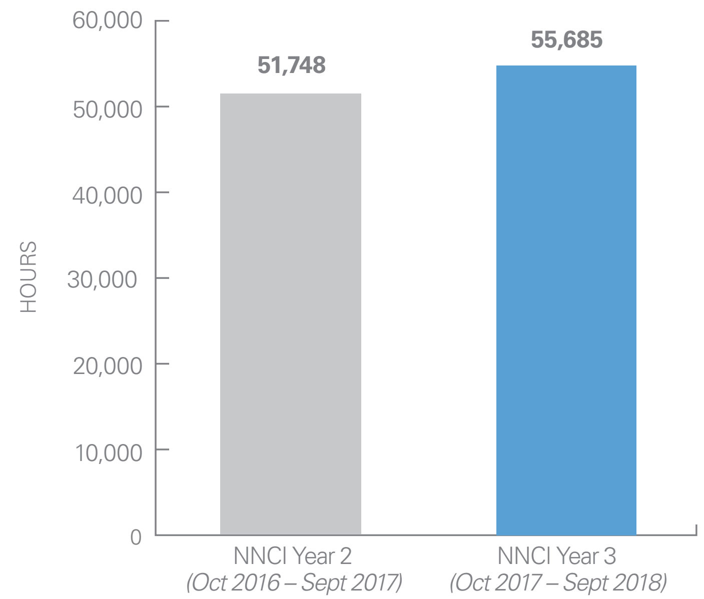
Slice from a DiceCT scan of an Indonesian tree shrew

Diffusible Iodine-based Contrast Enhanced Computed Tomography (DiceCT) is a method published and widely developed in the last 5 years for enhancing detail in micro-CT scanned biological samples. The method uses low concentrations of iodine solution that diffuse into the soft tissue of these samples; the radiopaque iodine differentially highlights muscles and connective tissue. These same tissues would often appear undifferentiated, and uninteresting, in traditional micro-CT scans, but the added contrast highlights areas previously only accessible by other types of imaging techniques (e.g., magnetic resonance imaging, MRI). The micro-CT lab has applied this method to several specimens including various mammals, invertebrates, isolated cadaveric material and histological samples.

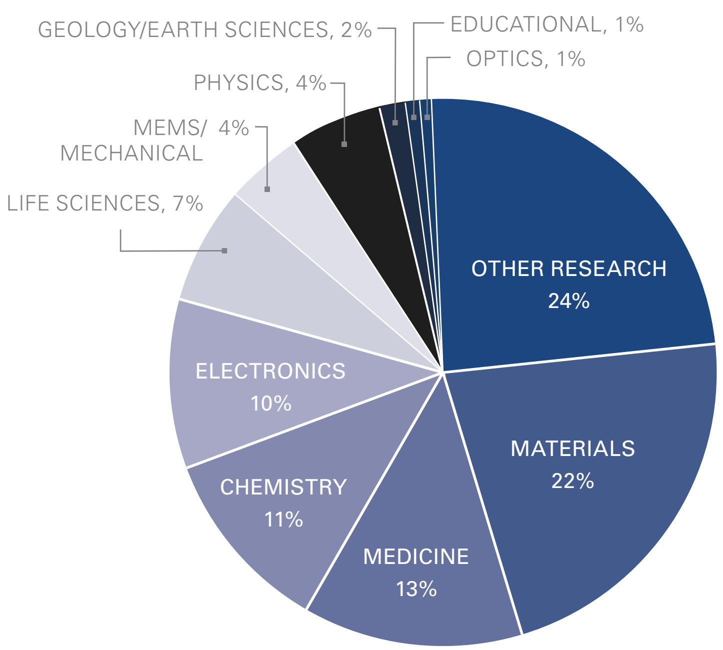
WHO USES RTNN?

In 2018, more than 1,300 unique users accessed the facilities for over 55,000 hours, an increase of 8% from the previous year. During this time, the RTNN trained almost 700 new users. RTNN currently draws the majority of its users from the host institutions (80%) and greater than 85% 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 external users' time in the facilities have been fruitful, with external researchers' hours growing from 8,694 to 9,249 over the past year.

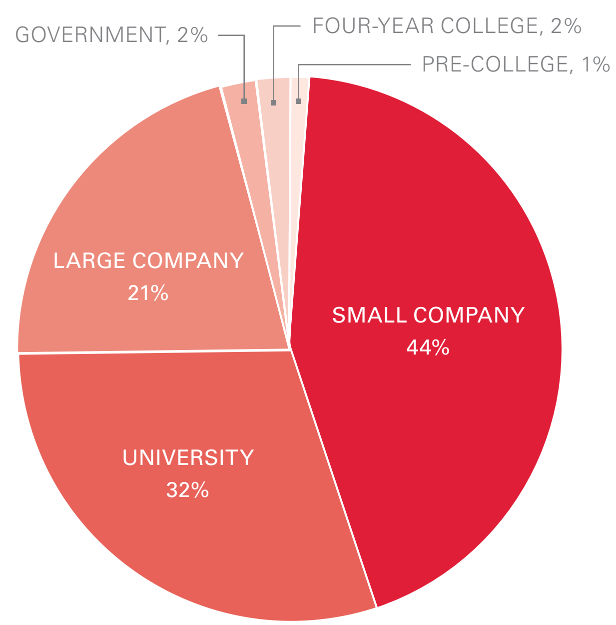
LAB TIME IN RTNN FACILITIES



ALL USERS BY DISCIPLINE



EXTERNAL USERS BY AFFILIATION



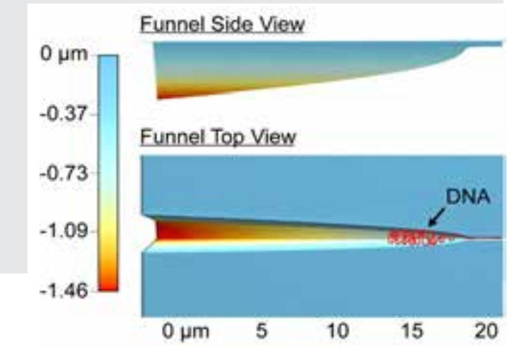
EXTERNAL USER HIGHLIGHT: GENTURI, INC.

Nanofluidic Platforms for Analyzing Genomic DNA

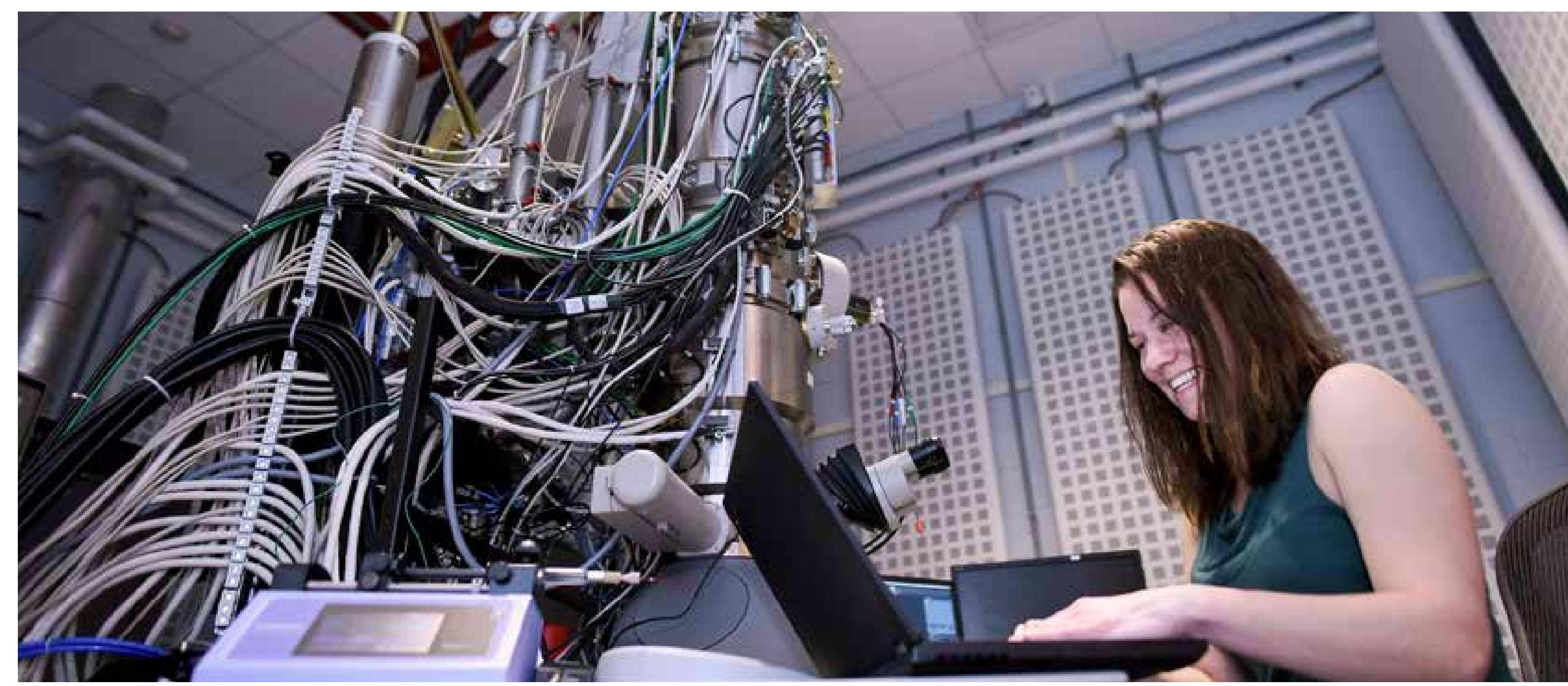
Genturi

Next generation sequencing enables a nearly whole-genome view of the single-nucleotide variants and small insertions, duplications, and deletions that contribute to an individual's genotype at a cost as low as $1,000. It performs poorly, however, at detecting larger mutations — portions of a genome that are rearranged or missing and that are known as structural variants — that play a significant role in various high-impact diseases. Genturi Inc. is developing nanofluidic platforms for isolating large genomic DNA molecules containing hundreds of thousands to millions of nucleotides and detecting structural variants in these molecules. Three-dimensional nanofunnels gently introduce DNA molecules into nanochannels where an enzyme cuts the molecules at sequence specific sites. The positions of these cuts are measured, revealing the long-range structure of the genome and the presence and identity of structural variants.

Publication: Zhou, J. et al. Enhanced nanochannel translocation and localization of genomic DNA molecules using three-dimensional nanofunnels. Nat. Commun., 8, 807 (2017).



AFM profiles of a three-dimensional nanochannel with a cartoon of DNA imposed on the top-view image.



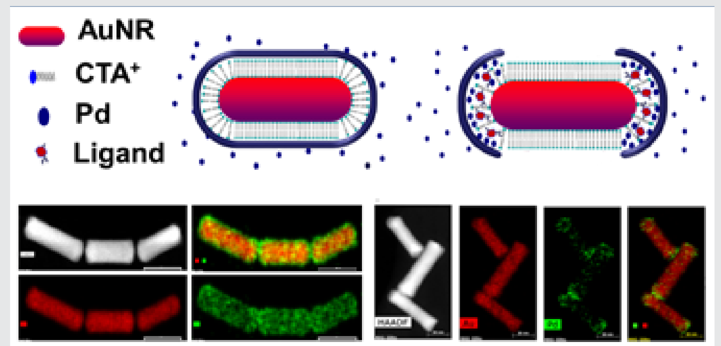
An external user sets up an in situ experiment on the Titan transmission electron microscope.

Anisotropic overgrowth of palladium on gold nanorods in the presence of salicylic acid family additives


Student: ***Nathalia Ortiz*** | *PI:* ***Gufeng Wang***
Department of Chemistry, North Carolina State University

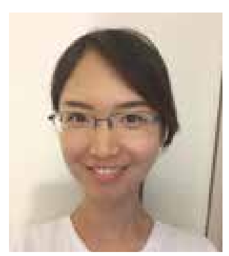
This work explored the use of salicylic acid family additives to CTAB to better control the growth of gold nanorods and palladium (Pd) capping. They found the optimal ratio of additive:CTAB to be 0.1-0.2. Using this ratio resulted in the longest gold nanorod length as well as a core-shell structure of Pd. At lower ratios, gold nanorods are unable to grow. At high ratios, the gold nanorods grow isotropically, disrupting the formation of a long, rod-like shape. Pd grows more randomly on these surfaces resulting in a non-uniform Pd cap. SEM images of the optimal nanorods show the Pd/Au distribution. This technology is currently being developed to produce hydrogen gas from solar light by capping the gold nanorods with platinum.

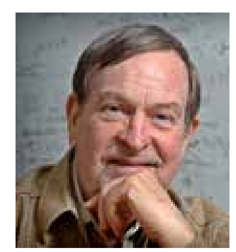
Publication: Ortiz, N. et al. Anisotropic Overgrowth of Palladium on Gold Nanorods in the Presence of Salicylic Acid Family Additives. J. Phys. Chem. C, 121, 1876–1883 (2017).



Pd overgrowth on gold nanorods (AuNRs) in the presence of optimal concentrations of SA family additives Bottom: EDS mapping of Pd (green) and Au (red) (Scale bar = 10 nm)

Photoelectrocatalytic water splitting by an integrated dye-sensitized photoelectrode

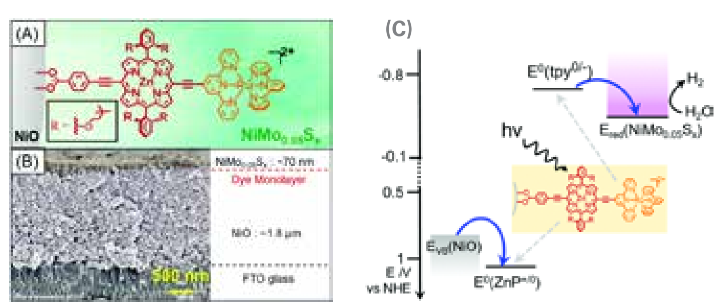




Students: ***Bing Shan*** *and* ***Animesh Nayak*** | *PI:* ***Thomas J. Meyer***
Department of Chemistry, University of North Carolina-Chapel Hill

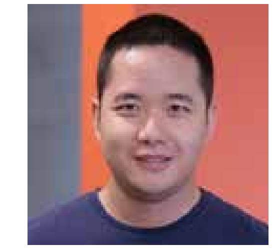
Dye-sensitized photoelectrodes combining surface-immobilized catalysts for water splitting or CO_2 reduction present a promising strategy for solar fuel generation. In this work, a new photocathode structure is designed based on a surface-bound supramolecular chromophore that generates a long-lived, redox-separated state directly at its excited state for transferring electrons to an electrodeposited, hydrogen evolution catalyst and holes to a p-type electrode substrate. The photocathode shows enhanced photoelectrocatalytic performances due to the direct catalyst activation by the excited state with the long-lived, redox-separated feature. The research used RTNN facilities for characterization of the photoelectrode by SEM and EDS.

Meyer, T.J. et al. Direct Photoactivation of a Nickel-Based, Water-Reduction Photocathode by a Highly Conjugated Supramolecular Chromophore. Energy Environ. Sci., 11, 447–455 (2018).



The structure **(A)** and cross-section scanning electron microscopic (SEM) image **(B)** of the photocathode. **(C)** Energy diagram illustrating the light-induced electron transfer reactions in the photocathode.

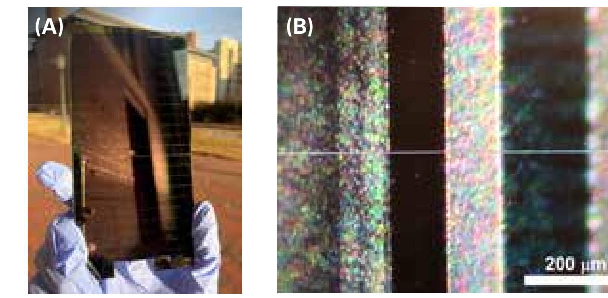
Scalable fabrication of organic-inorganic hybrid perovskite solar module




Student: ***Yehao Deng*** | *PI:* ***Jinsong Huang***
Department of Applied Physical Sciences, University of North Carolina – Chapel Hill

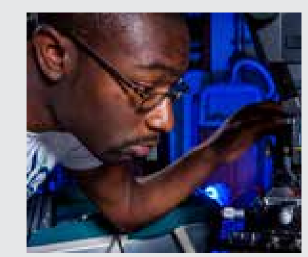
Organic-inorganic hybrid perovskites are novel photovoltaic materials with high power conversion efficiency over 22% and low-cost solution processing. However, scaling up of perovskite fabrication remains a challenge due to the complex fluid dynamics within perovskite precursor solutions when drying. The Huang group has successfully controlled the fluid dynamics by introducing a surfactant as an additive and demonstrated large area (>60 cm²) high quality perovskite films. Electrodes were first thermally evaporated onto perovskite films. Then, using a laser ablation system, these perovskite films were patterned into strips and connected in series to complete perovskite solar module fabrication with efficiency approaching 15.0%.

Deng, Y., et al., Surfactant-controlled ink drying enables high-speed deposition of perovskite films for efficient photovoltaic modules. Nat. Energy, 3, 560-566 (2018).



(A) A perovskite solar module. **(B)** Optical micrograph of laser scribed lines on perovskite solar module

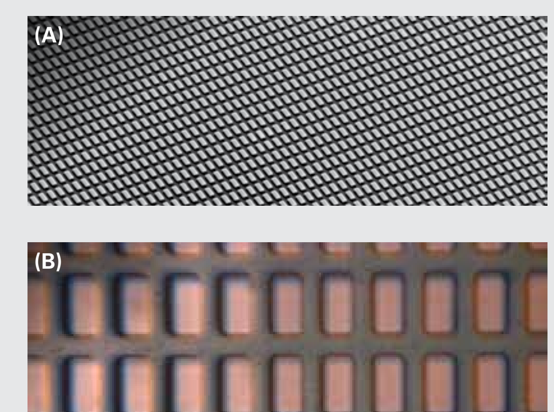
Dynamically reconfigurable active thin film silicon microparticles




Student: ***Ugonna Ohiri*** | *PIs:* ***Nan Jokerst*** *and* ***Orlin Velev***
Department of Electrical & Computer Engineering, Duke University

Thin film semiconductor microparticles have been engineered that demonstrate reconfigurable properties in electrically powered fluids. Particularly, Ohiri and colleagues have designed, fabricated, and powered millions of custom silicon microparticles, p-n junctions, and microdiodes that are 10 μm by 20 μm in surface area and 3.5 μm thick (100 times smaller than commercial devices that have been previously reported). These microparticles were fabricated on standard Silicon-on-Insulator (SOI) technology, using processes such as diffusion, metal deposition, lithography, and substrate release techniques developed by the Jokerst Lab over the past 25 years. Experimentally, these active microparticles can also dynamically assemble, disassemble, and reassemble on-demand when applying AC electric field gradients.

Publication: Ohiri, U. et al. Reconfigurable engineered motile semiconductor microparticles. Nat. Commun., 9, 1791 (2018).



(A) Optical micrograph of etched monodisperse 10 μm x 20 μm x 3.5 μm p-n junction silicon microparticles on SOI.

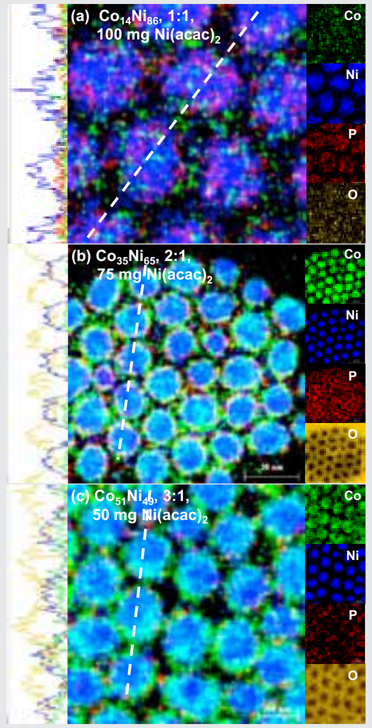
(B) Scanning electron micrograph of etched monodisperse p-n junction silicon microparticles.

Size and composition control of CoNi nanoparticles and their conversion into phosphides

In this work, binary CoNi nanoparticles were synthesized in a controlled manner by heating mixtures of Ni $(acac)_2$ and Co $(acac)_2$ (acac = acetylacetonate), oleylamine, trioctylphosphine, and trioctylphosphine oxide. By varying the amounts of Co and Ni precursors, the size of the nanoparticles could be controlled. The resulting particles are enriched with Ni when compared to the Co:Ni ratio of the precursors with Co localizing to the nanoparticle shells. If the reaction mixture is heated to 300˚C during synthesis, trioctylphosphone decomposes forming branched nanoparticles enriched with cobalt. The synthesis strategy adapted in this work forms the groundwork for synthesizing more complex phosphide nanoparticles.

Publication: Marusak, K. et al. Size and Composition Control of CoNi Nanoparticles and Their Conversion into Phosphides. Chem. Mater. 29, 2739-2747 (2017).

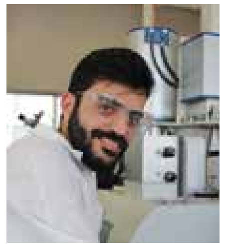
Undergraduate Student: ***Katherine Marusak***
PI: ***Dr. Joseph Tracy***
Department of Materials Science and Engineering, North Carolina State University



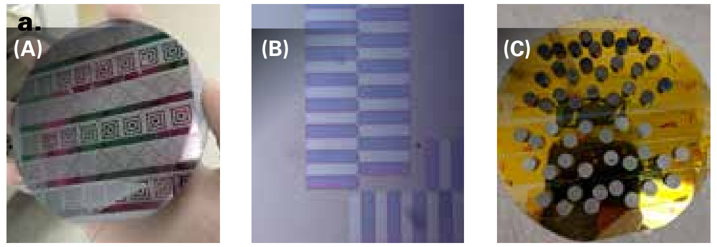
EDS maps of three selected samples of similar sizes and different compositions synthesized using Co:Ni precursor mass ratios of **(A)** 1:1, **(B)** 2:1, and **(C)** 3:1: (left) line scans, (center) composite EDS maps (excluding oxygen), and (right) EDS maps over the same region from which the composite images were composed.

Thermoelectric generators for self-powered wearable health monitoring systems

A team from the Nanoscience and Quantum Engineering Research Group has been developing a novel device structure that enables high-efficiency thin-film thermoelectric devices specially designed for power generation from small temperature gradients, as low as a few degrees, such as human body temperature. In contrast to conventional devices that are made of only dozens of millimeter-scale thermoelectric elements, the new device consists of several thousand micro-scale elements and can generate >1,000X larger voltage from a similar temperature gradient. The objective of this work is to develop a CMOS (complementary metal–oxide–semiconductor) compatible, wafer-scale microfabrication process that relies on mature processes and techniques used in micro-electro-mechanical-systems integration. A provisional patent application was recently filed for this technology. The team has also been working on optimizing materials for room temperature applications. Nanostructuring and new doping strategies enabled synthesizing materials optimum for body heat harvesting for self-powered wearable applications.



Students: ***Abhishek Malhotra, Prithu Bhatnagar*** | *PI:* ***Daryoosh Vashaee***
Department of Electrical and Computer Engineering, North Carolina State University

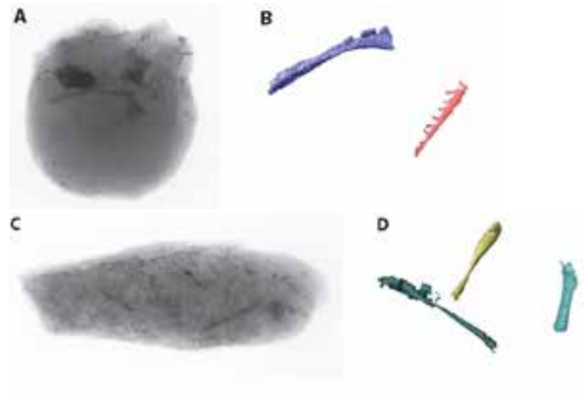


(A) Thermoelectric rings post spin-on doping process **(B)** Microscopic view of the n and p legs before metallization **(C)** Thermoelectric wafers mounted for the sputtering step

Analyzing computed tomography data from Late Triassic coprolites of Wingate Mesa, Utah

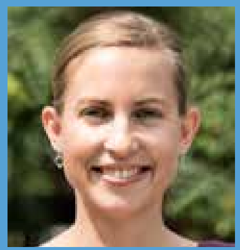
The purpose of this research was to determine the dietary habits of the coprolite (fossilized feces) culprits. The coprolites were collected from an understudied area in southeastern Utah with age-equivalent rock formations in Arizona, New Mexico, and Colorado. Determining the dietary habits of the coprolite culprits could help narrow down the range of animals that could have produced them from known vertebrate assemblages of the age-equivalent formations in other states. The data collected through CT scanning shows fish jaws, many fish scales, and what we identified as possible limb bones. The dietary content provides clear evidence that the culprits were aquatic or semi-aquatic animals.

Student: ***Yanelis Delgado*** | *PI:* ***Andrew B. Heckert****, PhD*
Department of Geological and Environmental Sciences, Appalachian State University

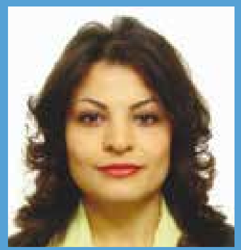


Two coprolite specimens with a few segmented contents from each, not including fish scales or other bone fragments that were seen in each one. **(A)**, **(C)** Coprolites with visible inclusions; **(B)** Segmentations of coprolite A that include a jaw fragment (purple) and a vein (pink) that formed as part of a diagenesis process which was later filled with minerals; **(D)** Bones segmented out of coprolite C with another jaw fragment (blue).

Collaborative Research Award



Khara Grieger



Maryam Khazaee

The collaborative research award recognizes users who are working with colleagues across at least two of the three RTNN institutions and utilizing RTNN facilities. In 2018, **Dr. Khara Grieger** and **Maryam Khazaee** were co-recipients of this award. **Khara** is an environmental scientist at RTI, International and won for her work, “Ensuring Sustainable Innovation of Water Treatment Technologies using Engineered Nanomaterials.” This project, a collaboration with Duke and NC State, supports the development of safe and sustainable water treatment systems that rely on engineered nanomaterials. This was performed through the selection, application, and testing of risk screening tools for a select group of nanomaterials proposed for use in water treatment technologies. **Maryam** is a Visiting Doctoral Researcher in the Department of Mechanical Engineering and Materials Science at Duke University. (Home Institution: University of Duisburg-Essen). Her project, “Fabrication and Characterization of Multidimensional Semiconducting Bismuth Halides for Electronic Applications,” was accomplished through collaboration and communication among scientists at Duke, NC State, UNC Chapel Hill, Dalhousie (Canada), and Duisburg-Essen (Germany).

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:

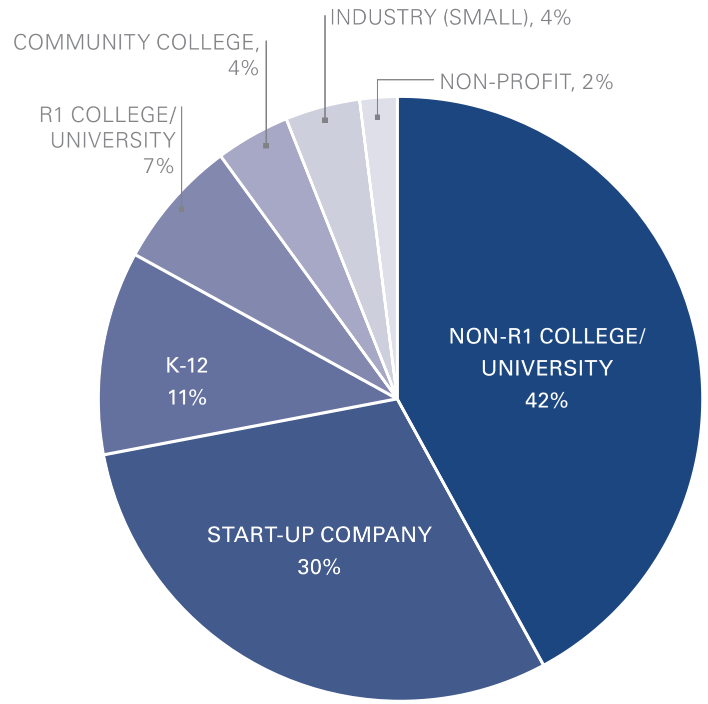
- **Knowledge** of the existence of the facilities and how to access them;
- **Distance** to travel to the facilities;
- **Cost** of accessing the facilities.

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 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. Over 50 projects have been selected for the Kickstarter program, receiving over 1,100 hours in facility use. The majority of participants hail from non-R1 colleges/universities, start-ups, and K-12 classrooms. **30% of participants in this program have continued to use facilities with their own financial support leading to an additional $70,000 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 these proposals.

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, >43,000 people have visited the course site and >9,000 have enrolled in the course.** The course has attracted learners from more than 130 countries across the world garnering scores of positive reviews. ***coursera.org/learn/nanotechnology***

RTNN student demonstrates plasma enhanced chemical vapor deposition in *Nanotechnology, A Maker's Course*

K-12 ENGAGEMENT

» **4,500 people reached in Year 3**

» **60% participation by underrepresented groups in STEM**

Girls STEM Day

On Saturday, May 19th, Girl Scouts and their families traveled to Duke University to learn from and work with over 100 women in STEM careers across the Triangle. Girl Scouts earned badges in digital photography, forensics, and robotics through a variety of different activities including use of SMIF's scanning electron microscope. In a parallel parents' forum, female STEM professionals, high school college counselors, and university admissions counselors engaged parents and troop leaders in interactive panel discussions.

Girl Scout examines her sample to earn a badge in digital photography during Girls STEM Day

Immersive Lab Experiences

The RTNN hosts many students throughout the year. In 2018, **over 1,100 students visited the facilities**. Our goal is to move beyond passive experiences such as tours of the facilities and demonstrations of the equipment to a more engaging experience. Thus, we have created immersive lab experiences for K-12 students. Here, students come to the facilities and work alongside other users. To prepare for the visit, students work outside the facilities including activities such as watching videos, collecting samples to image, or designing a photomask. In the facilities, students operate the equipment and take ownership of the work. Thus far, five user experiences have been designed: microcomputed tomography (micro-CT), electromagnetism, scanning electron microscopy (SEM), photolithography, and nanoparticle synthesis. Simple, one-page descriptions for teachers outline the program and how to get started.

RTNN visitors practice gowning up for the cleanroom

Visits to Classrooms

RTNN staff have also traveled to many K-12 classrooms and schools to introduce nanotechnology, interacting with over **1,100 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. In March 2018, RTNN staff traveled to Fayetteville, North Carolina to engage with science classes at John Griffin Middle School. Fayetteville is home to Fort Bragg, one of the largest army bases in the United States. The majority of John Griffin students have at least one parent actively serving in the military. Over three days, more than 600 6-8th grade science students learned more about nanotechnology and had the opportunity to use the desktop SEM

Middle school students learn more about the desktop SEM

Science Celebrations

The NC Science Festival includes events across the state at K-12 schools, museums, universities, parks, etc. In 2018, RTNN participated in these events in a number of ways. We sponsored NanoDays, which takes place annually at NC State. In addition to facilitating the event, we offered lab tours and conducted nanotechnology demonstrations. At this event, RTNN staff introduced the facilities, demonstrated different techniques, and provided hands-on activities. We also participated in several STEM fairs and expos locally and nationally, hosting **RTNN booths for >2,300 visitors** with hands-on activities related to nanotechnology.

High school students make "nano" ice cream during NanoDays

NNCI REU Convocation

In August, the RTNN welcomed over 50 guests to Raleigh at the annual NNCI REU Convocation. Participants came from 10 NNCI sites across the country to share their summer research projects with their peers as well as RTNN faculty, staff, and students. The event kicked off with a scavenger hunt where students searched NC State for a variety of landmarks. Attendees also participated in professional development activities that included updating their LinkedIn profiles and learning how to effectively communicate science to the public. Poster sessions were held on the campuses of Duke and UNC to give students a broader perspective of nanotechnology in the Research Triangle.

Attendees of the 2018 NNCI REU Convocation

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.

Workshops for Educators

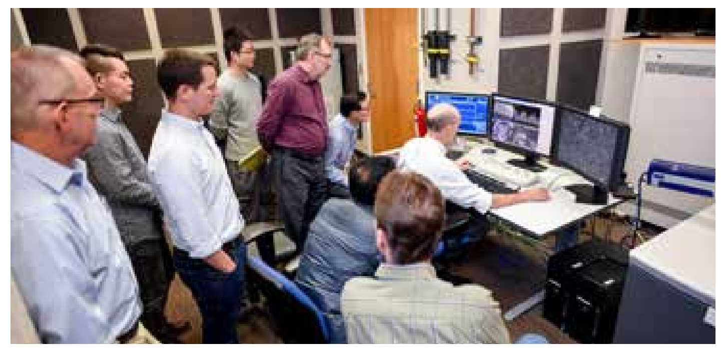
The RTNN held its third two-day nanotechnology workshop for community college and small college educators in August 2018. Participants operated multiple tools in the cleanroom to fabricate a working LED device and spent time incorporating nanotechnology instruments and techniques into their community college curricula.

We also held short workshops for local K-12 educators. These workshops inform educators of the numerous ways that they can interact with the facilities. During the event, educators get a tour of the facilities and demonstrations to give them a better sense of what is possible. Educators receive continuing education credits for their participation.

Community college educator observing the LED device that participants fabricated in the cleanroom

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 2018, RTNN held **27 workshops and short courses with over 140 participants**



Participants in an RTNN workshop

Student Outreach Awards

This award recognizes students who have dedicated their time to support RTNN education, outreach, and engagement activities. It shows our appreciation to the energy that these students have devoted to bringing in a future generation of users. **Justin Norkett** (NC State), **Nicole Smiddy** (UNC), and **Maxine Gorelick** (Duke) were the 2018 recipients of this award.

Nicole Smiddy

Justin Norkett

NANOTECHNOLOGY LEADERSHIP IN THE TRIANGLE

The RTNN works with other community organizations to promote nanotechnology in the Triangle. We work with community college educators and other local educators to help them to 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.

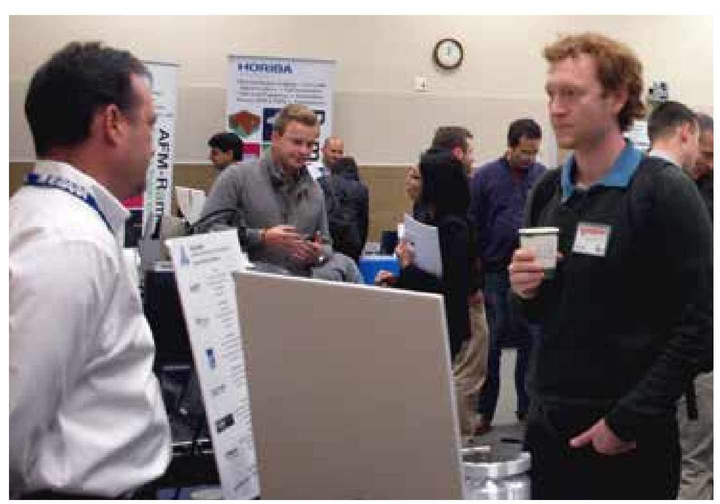
A young library patron practices her photolithography technique during National Nanotechnology Day

The RTNN is also working to connect researchers on emerging scientific topics at the forefront of nanotechnology. For example, in March 2016 the National Nanotechnology Initiative (NNI) issued a new Nanotechnology Signature Initiative (NSI) entitled "Water Sustainability through Nanotechnology: Nanoscale Solutions for a Global-Scale Challenge." In response, RTNN brought together an interdisciplinary group and led a proposal for NC State's Game-Changing Research Incentive Program (GRIP). The group received the $575k award in December 2016. This award currently supports several graduate students and researchers and has led to several publications and new research proposals

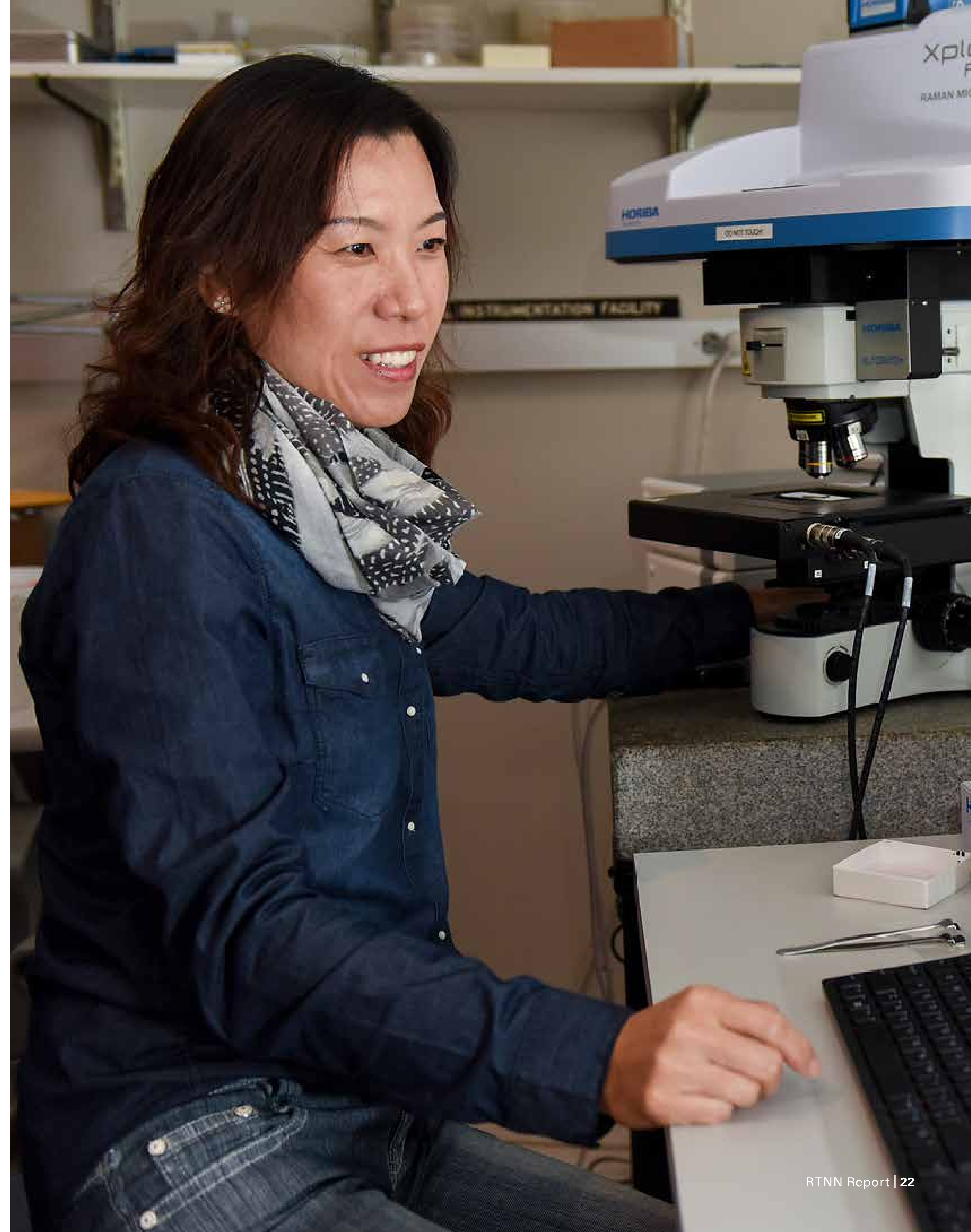
We actively seek out opportunities to strengthen and broaden our capabilities including proposals for: Research Experience for Teachers, Research Experience for Undergraduates, and Major Research Instrumentation at all three institutions.

In honor of National Nanotechnology Day, the RTNN hosted a nanotechnology-focused event at the Chapel Hill Public Library. Visitors were invited to explore science at the nanoscale by participating in a variety of hands-on activities. Library patrons tried on cleanroom suits, made "nano" ice cream, designed photomasks, examined samples with light microscopes, and more! Participants and volunteers had a blast celebrating the nanometer and learning from each other. We will return to the library in April 2019 with the desktop SEM in tow during the North Carolina Science Festival.

Each fall, the RTNN helps to organize the Carolina Science Symposium. This student-focused conference gives many early career students their first opportunity to present their research in a professional setting. The event gives attendees the chance to practice and perfect their presentation skills, network with their peers, and learn about the facilities and tools available within the RTNN. Over 100 attendees from across North Carolina participated this year, and attendance continues to grow each year.



Carolina Science Symposium attendees deep in conversation



NATIONAL IMPACT AND ENGAGEMENT

The RTNN is actively involved in NNCI working groups and committees.

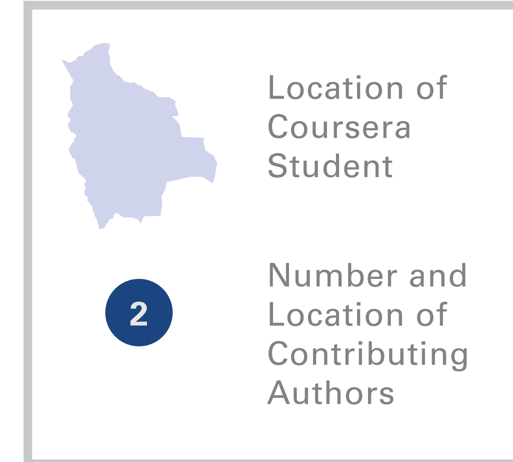
In August, RTNN hosted more than 50 REU students as well as faculty and staff from 10 NNCI sites across the country.

We also used our expertise to guide assessment strategies for other sites, and our effort to reach out to Spanish speakers has been replicated nationally via an ¿Habla español? button on the NNCI website.

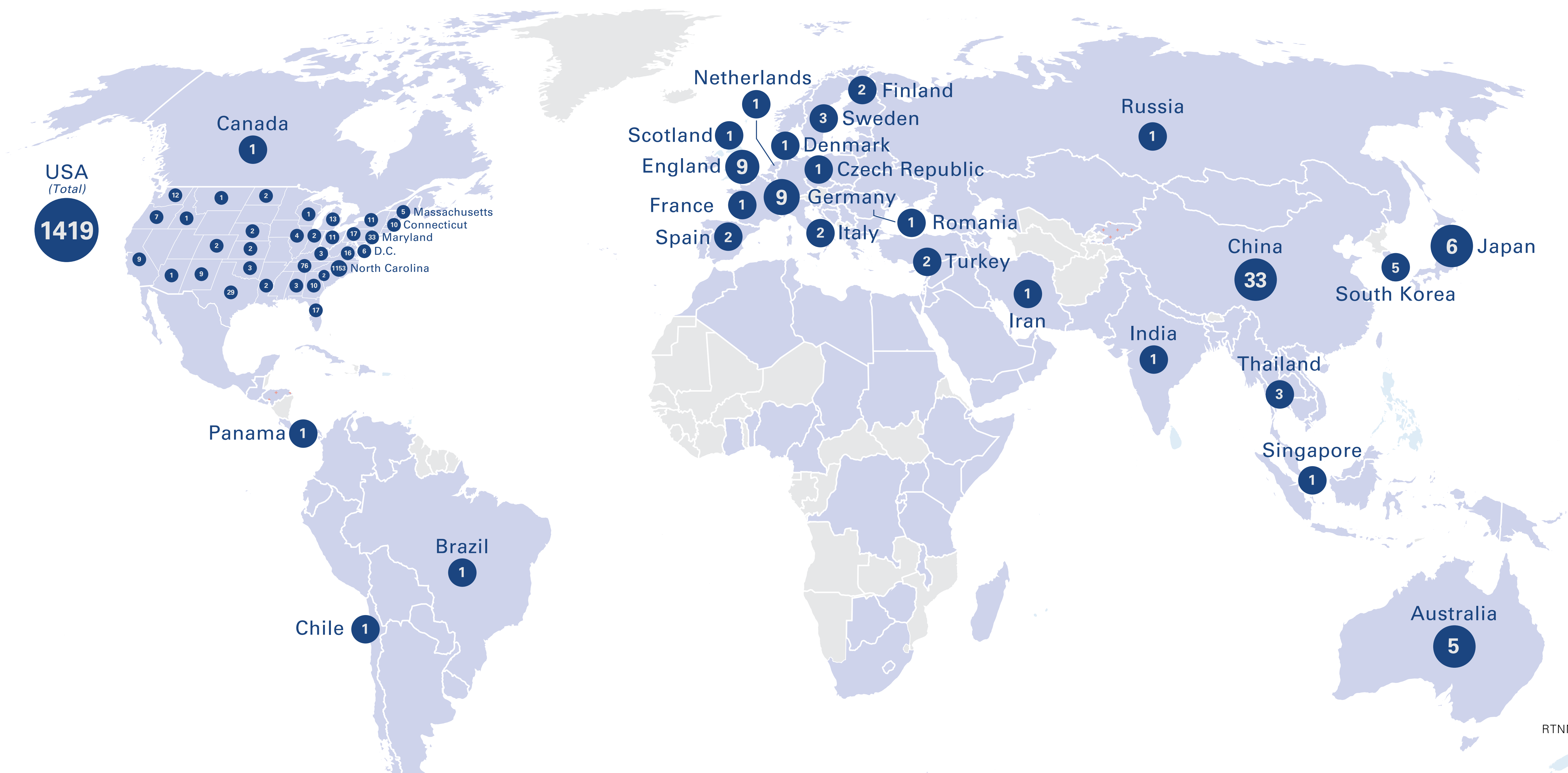
Our staff attend diverse national events and conferences, including the USA Science and Engineering Festival, to raise awareness of RTNN and NNCI's educational and technical programs.

We partner with Remotely Accessible Instruments for Nanotechnology (RAIN) to bring our remote access capabilities to a national stage.

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



GLOBAL REACH



NANOTECHNOLOGY OUTCOMES

OUTCOME NUMBERS

$83 Million in research activity, as defined by annual research expenditures, for projects that utilized the facilities

12 Patents awarded

40 Invention disclosures

39 Patents filed

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

Kickstarter program feedback

To assess the Kickstarter program, semi-structured interviews have been conducted with 13 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.

> **"...there's a small group of us that are out trying to develop new ideas and kind of unconventional ways to do things. So I'm already telling them about [the Kickstarter Program]."**

Nanotechnology, A Maker's Course

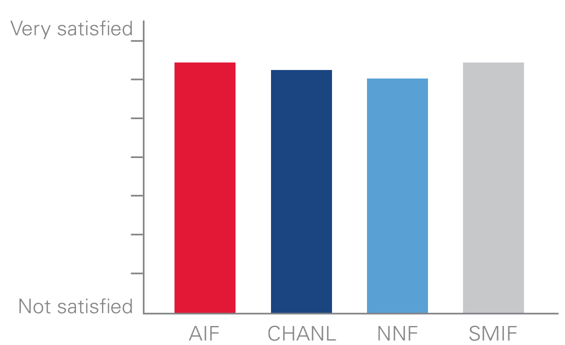
After completing the course, students receive a survey through the Coursera platform. Overall, students were very satisfied with the course. **93% of respondents** noted that they were *likely* or *very likely* to recommend the course to others. **91% of respondents** noted that they had a better knowledge of the capabilities of RTNN's facilities.

Immersive lab experiences

We obtained IRB approval to survey K-12 students who participated in our SEM immersive lab experience. The survey consisted of two parts. We first asked the students to give us a grade from F to A+ assessing their overall experience, the labs, and the staff. We then asked the students to tell a story about their experience. **The overall experience got an average grade of A-; the labs an A-; and the staff an A**. The students' stories communicated the benefits of the first-hand experience and interpersonal communication between staff and the students. Even small interactions left bright impressions.

User assessment: satisfaction

All users received an online RTNN 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 99 percent of users indicated that they would return to the lab if further work was necessary**.



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

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Visit us online	**rtnn.org**
Sign up for our newsletter	**rtnn.ncsu.edu/contact-us**

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