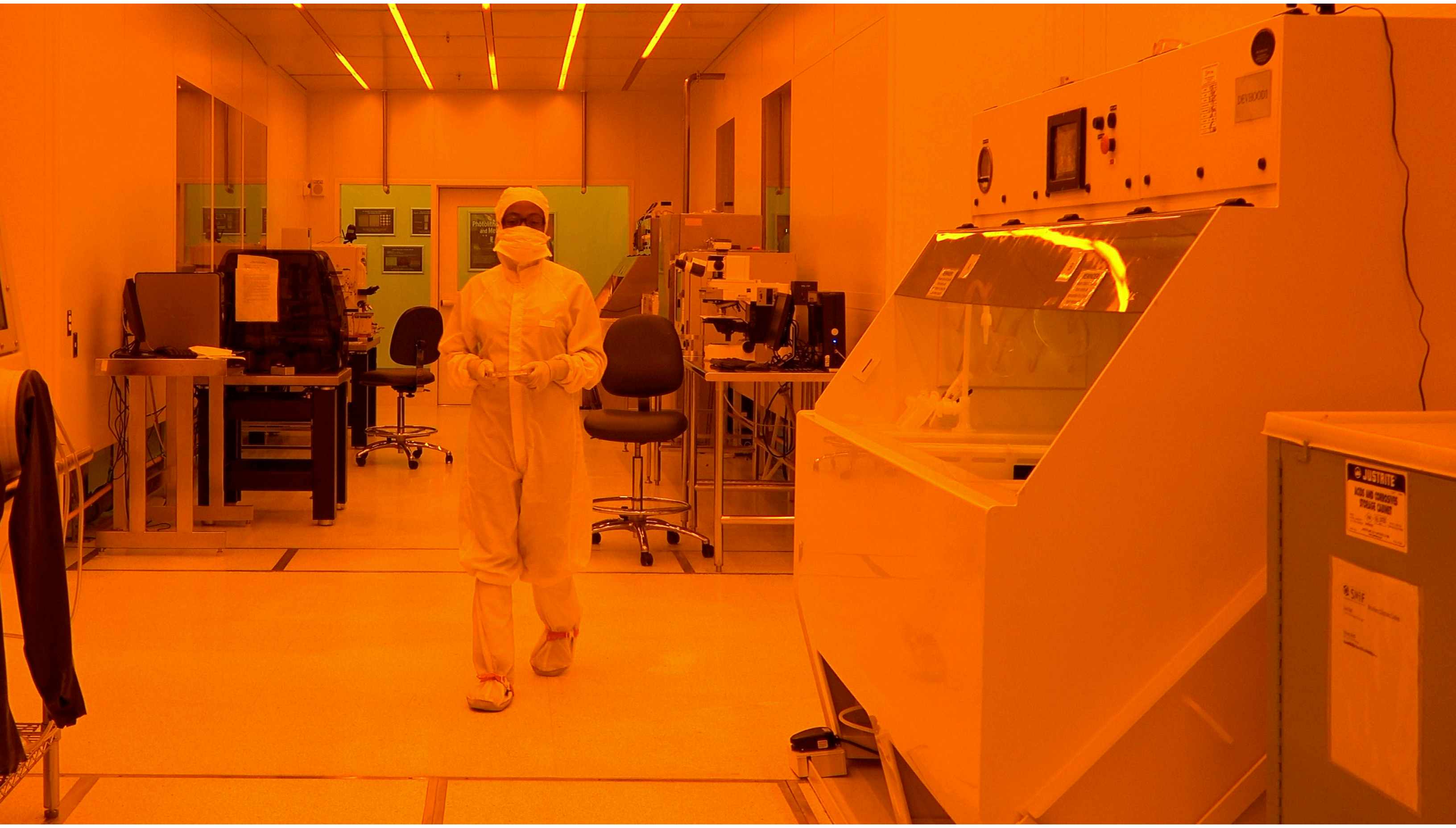
RTNN

RESEARCH TRIANGLE NANOTECHNOLOGY NETWORK

2017 REPORT



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NSF

National Nanotechnology Coordinated Infrastructure

TABLE OF CONTENTS

02 About

04 Core Facilities

08 New Tools and Capabilities

10 Who Uses the RTNN?

14 Research and Development Highlights

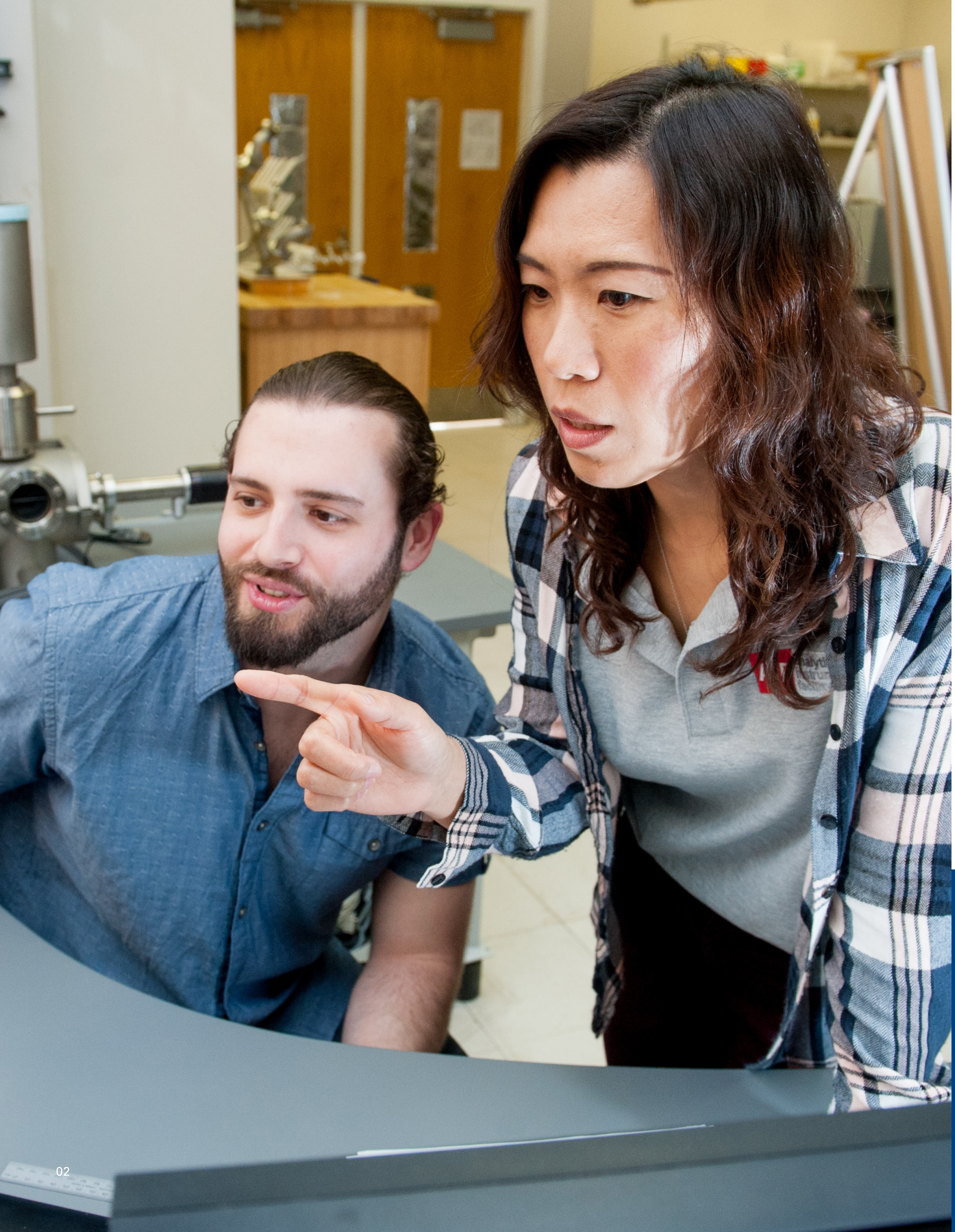
18 Outreach Highlights

24 Nanotechnology Leadership in the Triangle

26 National Impact and Engagement

28 Nanotechnology Outcomes

29 Getting Started with RTNN



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 such site.

The RTNN is a 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 core nano-fabrication and characterization facilities and more than 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 programming, the RTNN is able to support and advance basic research at the nanoscale as well as the development and commercialization of innovative nanotechnologies.

Program Highlights

Our activities are designed to expand the awareness of nanotechnology, our facilities, and how they can be accessed. These activities are innovative, comprehensive, and effective with continual assessment and revision. Highlights from the past year include:

- **The Kickstarter Program** provided ~400 hours on nanotech tools to 18 new and non-traditional users
- **Nanotechnology: A Maker's Course**, a Coursera online course, was launched in September and enrolled more than 2,500 students
- RTNN visited regional K-12 classrooms to give more than 1,000 students training and hands-on experience like operating a **portable scanning electron microscope (SEM)**
- More than 1,800 K-12 students participated in **hands-on experiences in RTNN facilities**
- Classrooms took **virtual field trips** to RTNN SEMs to view student-collected samples
- **Community college faculty members** visited the RTNN to attend the second annual nanotechnology workshop for educators, designed to give them time to use nanotechnology tools and develop curriculum founded in nanotechnology concepts
- **32 technical workshops and short courses** exposed more than 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 more than eight 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 cleanroom fabrication and characterization capabilities for research in bio/soft matter nanoscience, environmental nanotechnology, heterogeneous integration, and metamaterials/plasmonics.

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.

BY THE NUMBERS

- **3** major research universities
- **9** core shared user facilities
- More than **40,000** sq. ft. of laboratory space
- More than **200** major fabrication and characterization tools
- More than **50** technical staff members
- More than **50,000** annual hours of collective use

Zeis Textiles Extension

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 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.

CEINT

The 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.

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

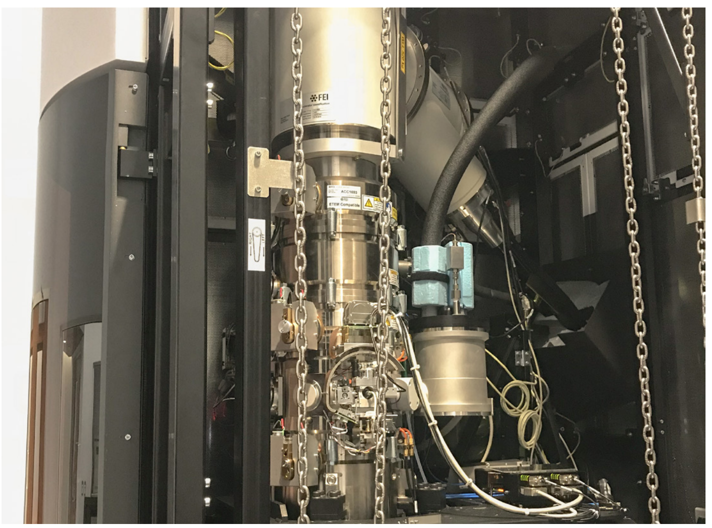
Specialized Equipment and Expertise

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)
- 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 Cryo-Transmission Electron Microscope:** This 300 keV instrument offers atomic scale resolution of samples held at cryogenic temperatures and is the most powerful and flexible high-resolution electron microscope for 2D and 3D characterization of biological samples on the market. Its cryo-based technology and stability allow for single particle analysis and dual-axis cellular tomography of frozen hydrated cell organelles and cells. The TEM is equipped with a robotic loader, capable of handling up to 12 frozen hydrated samples, for increased throughput.



Looking inside the new FEI Titan Krios.

- **Asylum MFP-3D Classic Atomic Force Microscope (AFM):** The instrument comes with a variety of advanced capabilities including variable magnetic field module for in- and out-of-plane measurements, a probe station adapter for concurrent 2- and 3-point probe electrical measurements, viscoelastic mapping mode, conductive AFM, and a closed fluid cell for measurement in gases or liquids.

- **XploRA PLUS Confocal Raman Microscope:** This instrument combines Raman spectroscopy and optical microscopy, providing sample identification and chemical imaging on a microscopic scale. The interaction of laser light with a sample results in a detailed chemical fingerprint. It offers fast confocal imaging and automated laser wavelength switching. It is a non-destructive, non-contact technique ideal for numerous samples: pharmaceuticals, semiconductors, polymers, etc. The instrument also hosts a variable temperature stage (-196 to 600˚C).

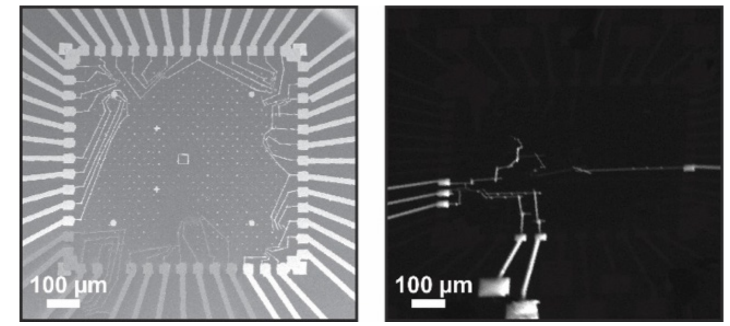
- **E-beam Lithography:** A new Nanometer Pattern Generation System (NPGS) was installed in one of our focused ion beam (FIB) systems. The NPGS is designed as an e-beam lithography system but can also be used with the FIB. The system can achieve patterning with resolution on the order of less than 20 nm for the electron beam and less than 50 nm for the ion beam.

- **Heidelberg Instruments µPG 101 Maskless Lithography System:** This direct write lithography system is equipped with a 375 nm ultraviolet diode laser capable of exposing feature sizes down to 0.8 µm on either positive or negative photoresists on sample sizes of 10 x 10 mm up to 5 x 5 inches. In addition to full exposure, it has the ability to create surface topographies for grayscale applications.

- **Horiba H-CLUE Spectroscopy & Imaging Catholuminescence (CL) system:** CL spectra can be collected at nanometer spatial resolution to probe electronic-structure inhomogeneities in materials. The technique can be used to induce and image surface plasmon resonances in nanostructured materials. The H-Clue offers wide spectral range from UV to IR, 200-2200 nm (6.2 – 0.56 eV). The technique is particularly suitable for analysis of wide-band semiconductors, photonic and polaritonic nanostructures, dielectric oxides, and minerals.

- **Annealsys AS-One 150 Rapid Thermal Processor:** This tool is capable of running samples from small pieces to 6″ wafers up to 1300˚C with pressure ranges from atmospheric conditions to high vacuum.

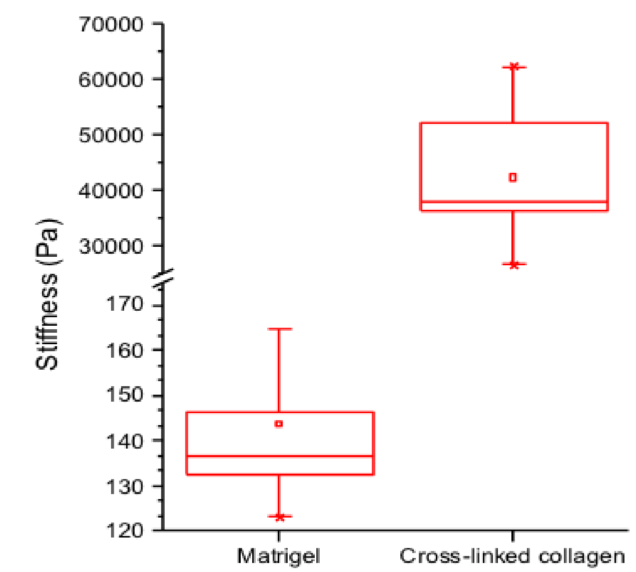
- **Voltage Contrast:** This technique allows users to clearly differentiate electrically connected components from disconnected components. Contrast occurs when the incident beam charges the floating/disconnected region on the sample causing it to appear brighter when imaged with the electron beam or darker when imaged with the ion beam. The regions of the sample that are electrically connected to the SEM ground are able to dissipate any charging and appear dark when imaged with the electron beam or bright when imaged with the ion beam. The simplicity of the process is ideal for quickly and precisely identifying failures in nanoscale electronic devices/integrated circuits, determining network connectivity in percolation networks, finding disconnected regions in thin films, and a variety of other applications.



Example of negative (left) and positive (right) voltage contrast resulting from charging with the electron beam and ion beam for two distinct circuits.

- **Air Sensitive X-ray and Ultraviolet Photoelectron Spectroscopy (XPS/UPS) Measurements:** Researchers in Scott Warren's group (UNC, Departments of Applied Physical Science and Chemistry) sought to study phosphorene (atomically thin layers of phosphorus). However, this material is extremely air sensitive and is typically handled in a nitrogen purged glovebox. Carefully controlled introduction of samples into the XPS chamber prevented oxidation of these samples and also allowed for controlled studies of the oxidation rate. This sample loading technique has also been successfully applied to air sensitive samples from other research groups. *Publication: Woomer, A. H. et al. Phosphorene: Synthesis, Scale-Up, and Quantitative Optical Spectroscopy. ACS Nano 9, 8869–8884 (2015).*

- **Elastic Modulus Measurements on Soft/Sticky Materials in Fluid:** Many RTNN researchers are studying soft and/or sticky materials. Often, these samples must be characterized in liquids to remain hydrated. By using large colloid probe tips with an atomic force microscope, we are able to extract elastic modulus values from these types of samples in fluid conditions. The Allbritton lab (Joint Department of Biomedical Engineering, UNC and NC State) is pursuing development and application of micro total analysis systems (microTAS) devices to recapitulate the microenvironments of the intestine, and recent measurements in CHANL have helped to determine the elastic moduli of the extracellular matrices used to support cell growth. These samples were soft and sticky and were measured in fluid to retain hydration. Other samples are also under investigation.



A comparison of stiffness values of a soft extracellular matrix (Matrigel) and fully chemically cross-linked calf-skin collagen.

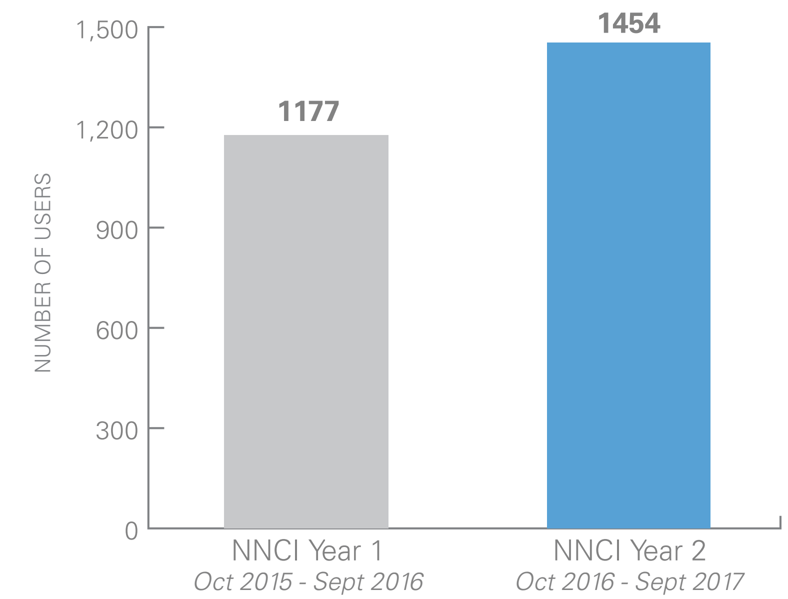
Molecular Microscopy Consortium

RTNN's FEI Krios joins the FEI Talos Arctica (located at the National Institute of Environmental Health Sciences, NIEHS) as part of the Molecular Microscopy Consortium (MMC) in the Research Triangle. This consortium is a partnership between NIEHS, Duke, and UNC. The mission of the MMC is to provide single particle cryo-electron microscopy (cryo-EM) and other tools in molecular microscopy to researchers across North Carolina. Cryo-EM is increasingly being used to determine the structure of macromolecules at atomic resolution. There is also emerging interest in applying the technology to the ultrastructure analysis of cellular compartments. The MMC was established to meet the growing demand for instrumentation and expertise in this area.

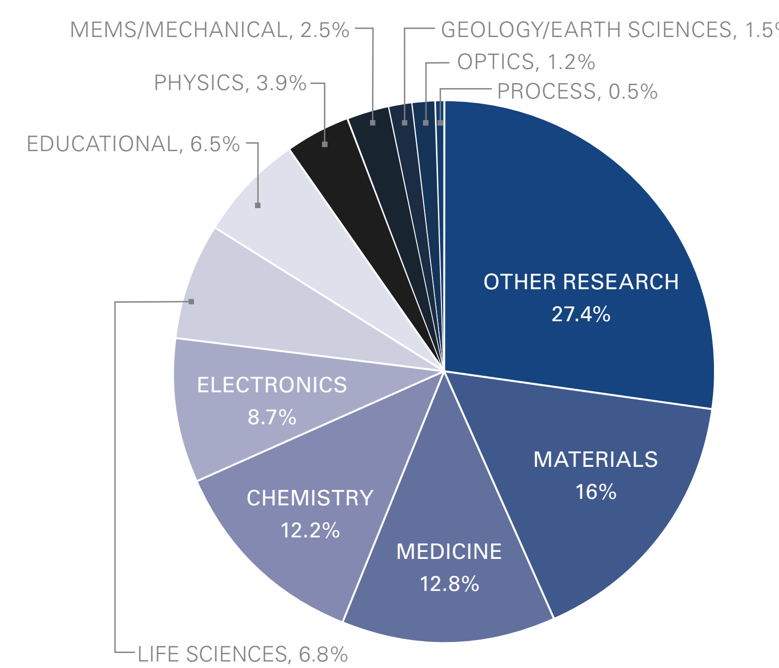
WHO USES RTNN?

In RTNN's 2nd year, more than 1,400 unique users accessed the facilities for greater than 51,000 hours. This exceeds our goal of 15 percent year over year growth in user number. During this time, the RTNN trained more than 500 new users. RTNN currently draws the majority of its users from the host institutions (80 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 bring in more industry clients in our 2nd year have been fruitful. We hosted 132 users from small companies and 85 users from large companies (up from 89 and 29 users respectively).

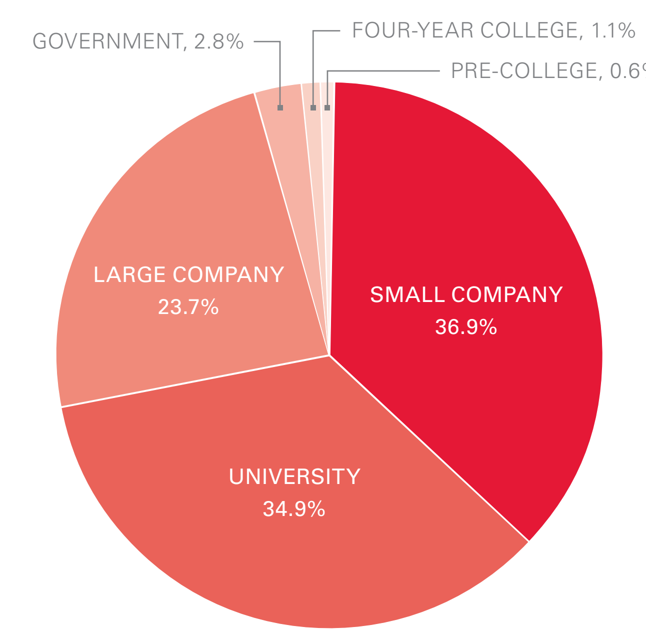
NUMBER OF UNIQUE USERS OF RTNN FACILITIES



ALL USERS BY DISCIPLINE



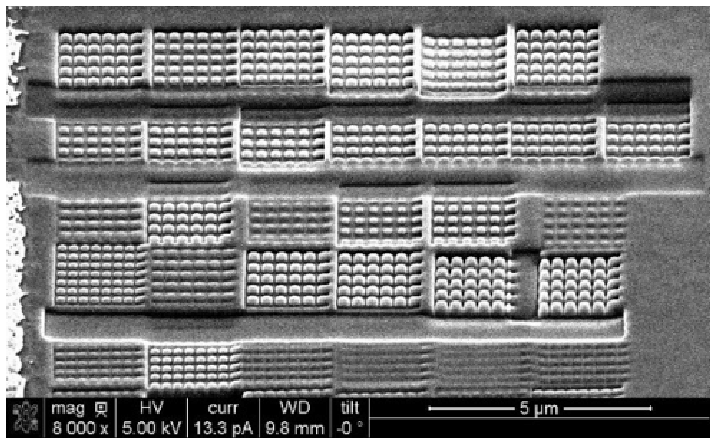
EXTERNAL USERS BY AFFILIATION



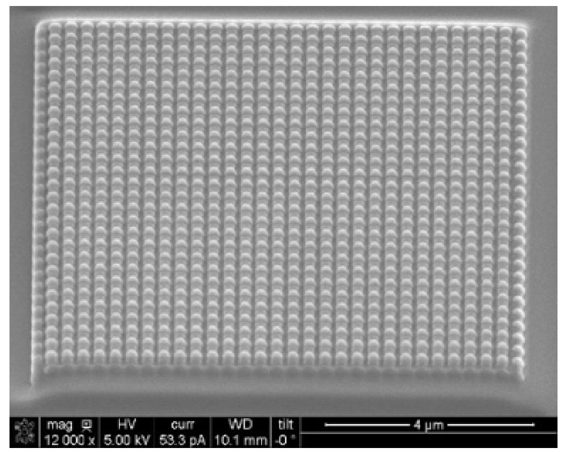
External User Highlight: Smart Material Solutions

Smart Material Solutions

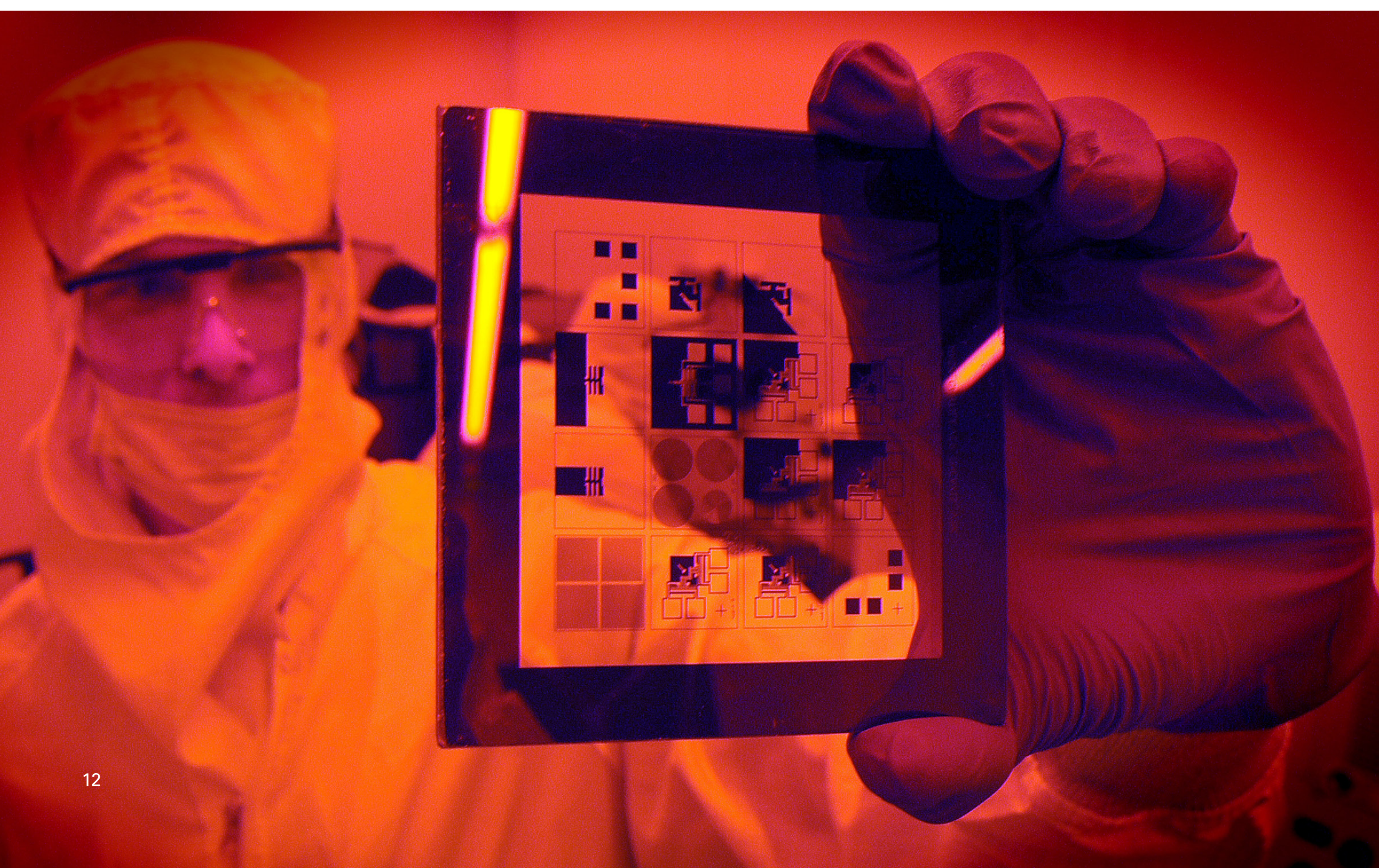
Nanocoining is a process whereby sub-wavelength structures are cut into the tip of a diamond die using a FIB. The die is then pressed into metal to rapidly create nano-structured surfaces. These features are invisible to the eye but can manipulate light or repel water. For example, the surface can be made anti-reflective to increase the energy of solar cells. FIB milling of 300 nm tall and 300 nm wide structures into diamond is a significant challenge because of many factors. Capitalizing on the Kickstarter program, the team optimized the milling parameters to create high-resolution, sub-micron structures in diamond. The results led to SBIR Phase II funding.



A number of test patterns were used to determine optimum beam parameters for cutting diamond.



Diamond die created using the nanocoining process.



Plasma-enhanced atomic layer deposition (PEALD) for deposition of ultra-thin high-κ films on 2D crystals

Regardless of the application, 2D crystals require the deposition of a high-κ dielectric, either for passivation or as part of the device. In this work, PEALD is used to grow common high-κ dielectrics, such as hafnium oxide and aluminum oxide, on 2D crystals as thin as ~ 3 nm – the thinnest film deposited to date without the addition of a buffer layer or extra functionalization steps. These ultra-thin films are integrated into the gate stack of a top gate molybdenum disulfide transistor and show superb switching and low gate leakage.

Price, K.M., Schauble, K.E., McGuire, F.A., Farmer, D.B., and Franklin, A.D. Uniform Growth of Sub-5-Nanometer High-κ Dielectrics on MoS_2 Using Plasma-Enhanced Atomic Layer Deposition. ACS Appl. Mater. Interfaces 9, 23072-23080 (2017).

*Student: **Katherine M. Price** | PI: **Aaron D. Franklin***
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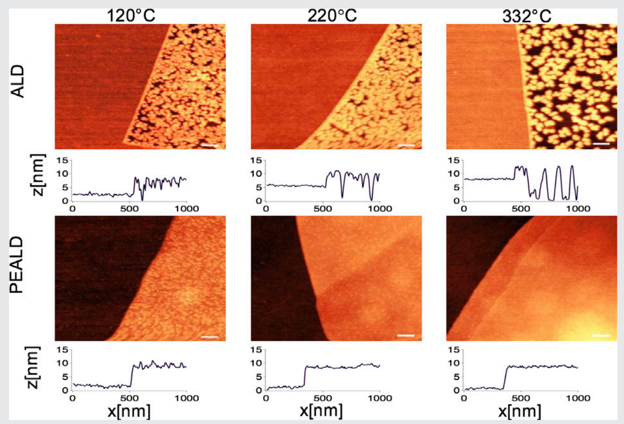
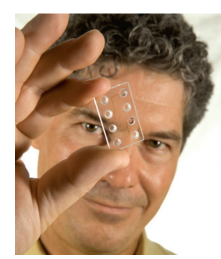


The difference between the more traditional method (ALD) of depositing films on MoS_2 (ALD) and the method used in this work (PEALD).

Photobleaching kinetics-based bead encoding for multiplexed bioassays

Multiplexing bead-based bioassays requires that each type of microsphere be uniquely encoded to distinguish one type from another. Microspheres are typically encoded using fluorescent dyes with different spectral properties and varying concentrations. However, practical limits exist on the number of dyes that can be spectrally resolved and the number of distinguishable intensity levels with each dye. To expand the number of encoding levels, a novel method was developed that incorporates photobleaching kinetics into bead decoding. Beads were encoded with two dyes having overlapping fluorescence excitation and emission wavelengths but different photostabilities. By comparing the original fluorescence emission intensity to that obtained after photobleaching, multiple different populations could be reliably identified. Using only a single excitation/emission band, two different initial intensity levels were optimized to produce six uniquely identifiable bead populations whereas only two could have been achieved with conventional decoding methods. Incorporation of this encoding strategy into bead-based microwell array assays significantly increases the number of encoding levels available for multiplexed assays without increasing the complexity of the imaging instrumentation.

Publication: Linz, T. H., Hampton Henley, W. & Michael Ramsey, J. Photobleaching kinetics-based bead encoding for multiplexed bioassays. Lab Chip 17, 1076–1082 (2017).



*Research Scientists: **Thomas Linz, W. Hampton Henley***
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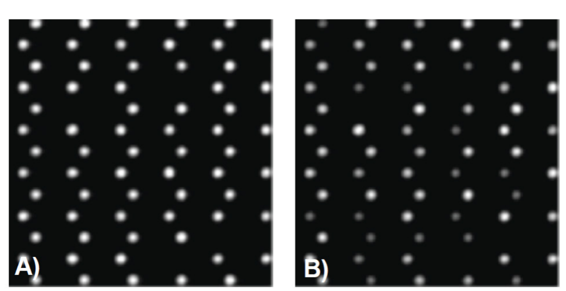


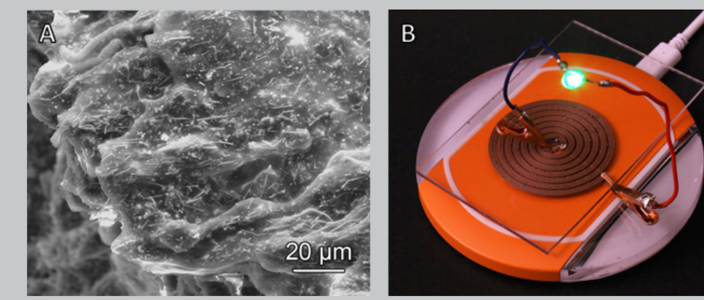
(a) All beads initially exhibited similar fluorescence intensities.
(b) After photo exposure, the less photostable dye had reduced emission intensity due to photobleaching.

Large-scale synthesis of Cu-Ag nanowires and its application in 3D printing filament

A large-scale synthesis of copper-silver core-shell nanowires (Cu-Ag NWs) was developed that is faster, greener, and reacts under milder conditions than previous synthetic methods. The Cu-Ag NWs were incorporated into PCL, a common 3D printing thermoplastic, to produce the most conductive 3D printing filament (0.002 Ω cm) compatible with standard desktop 3D printers. This work aims to develop practical methods for printing electronic devices without the need for expensive, specialized printers.

Cruz, M.A., Ye, S., Kim, M.J., Reyes, C., Yang, F., Flowers, P.F., Wiley, B.J., "Multigram Synthesis of Cu- Ag Core–Shell Nanowires Enables the Production of a Highly Conductive Polymer Filament for 3D Printing Electronics," Part. Part. Syst. Charact. 2018, 1700385.

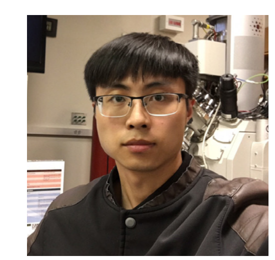
*Student: **Mutya Cruz** | PI: **Benjamin Wiley***
Department of Chemistry, Duke University



A: SEM image of the conductive filament showing even distribution of Cu-Ag NWs throughout the PCL thermoplastic.
B: An inductive charging coil was 3D printed using the Cu-Ag NW filament and powered an LED when paired with a wireless charging dock.

Tunable nanostructures with dynamic optical properties

This work is focused on making nano-pillar array structures, which are mixed with magnetic particles such as Ni, Co, and Fe_3O_4. The structures have different reflectivity, namely different colors, when pillar arrays are actuated to tilt to a certain angle. Having feature sizes smaller than the wavelength of light, the proposed tunable surface nanostructure can be widely applied to any surfaces. This research will greatly enhance capabilities in adaptive camouflage that can simultaneously change color, surface texture, and reflectivity, which can be widely applied to clothing, vehicle, and infrastructure surfaces.



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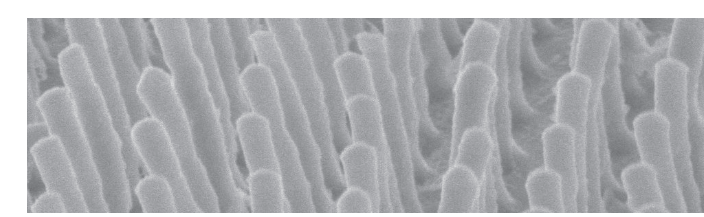


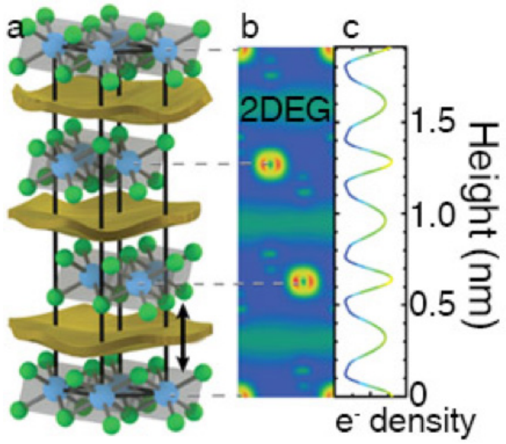
SEM image of the magnetic nano-pillar array. The pillar height is ~ 4.9 µm, and the diameter is ~ 0.5 µm.

Experimental demonstration of an electride as a 2D material

Ca_2N, a layered material, has an enormous 4 Ångstrom gap between layers. This gap is filled by an exotic, highly conductive cloud of electrons. The Warren lab has now reported that it is possible to pull apart these layers, yielding a 2D material that still retains the electron cloud. The result is a 2D material that is more conductive and more transparent than graphene. Ca_2N is a type of ionic solid called an electride. In electrides, the “anion” is not a negatively charged atom but is, instead, simply an electron without a nucleus. In Ca_2N, the electrons are grouped into layers where their wave function overlaps, giving metallic character. This is called a 2D electron gas (2DEG). We attempted to exfoliate Ca_2N in a wide variety of solvents. To our surprise, Ca_2N was unstable in tetrahydrofuran but exhibited long term stability in 1,3-dioxolane. With 2D Ca_2N now available, numerous studies into the chemical and physical behavior are now possible.

Publication: Druffel, D. L. et al. Experimental Demonstration of an Electride as a 2D Material. J. Am. Chem. Soc. 138, 16089–16094 (2016).

*Research Scientist: **Daniel Druffel***
*PI: **Scott Warren***
Departments of Chemistry and Applied Physical Sciences, University of North Carolina – Chapel Hill



(a) Structure of Ca_2N

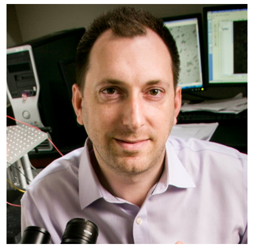
(b) Density functional theory calculation of electron density

(c) Integrated height profile of the electron density

Magnetic microfluidic circuits for organizing bio-particle arrays

Magnetic microfluidic circuits are used to manipulate single particles and living cells in microchips. The chip is composed of hydrodynamic traps as well as magnetic circuits. The particles of interest are first flowed inside microfluidics channels and caught in the hydrodynamic traps. Next, appropriate magnetic field is produced by the magnetic circuits, moving the trapped particles into storage sites. Moreover, the chip is capable of organizing single cells and cell pairs in microfluidic storage sites of an array. Once assembled, it is possible to study cell-cell interactions and their protein secretion profiles.

Publications: Abedini-Nassab, R. et al. Magnetophoretic Conductors and Diodes in a 3D Magnetic Field. Adv. Funct. Mater. 26, 4026–4034 (2016).; Abedini-Nassab, R. et al. Characterizing the Switching Thresholds of Magnetophoretic Transistors. Adv. Mater. 27, 6176–6180 (2015).; Abedini-Nassab, R. et al. Magnetophoretic transistors in a tri-axial magnetic field. Lab Chip 16, 4181–4188 (2016).



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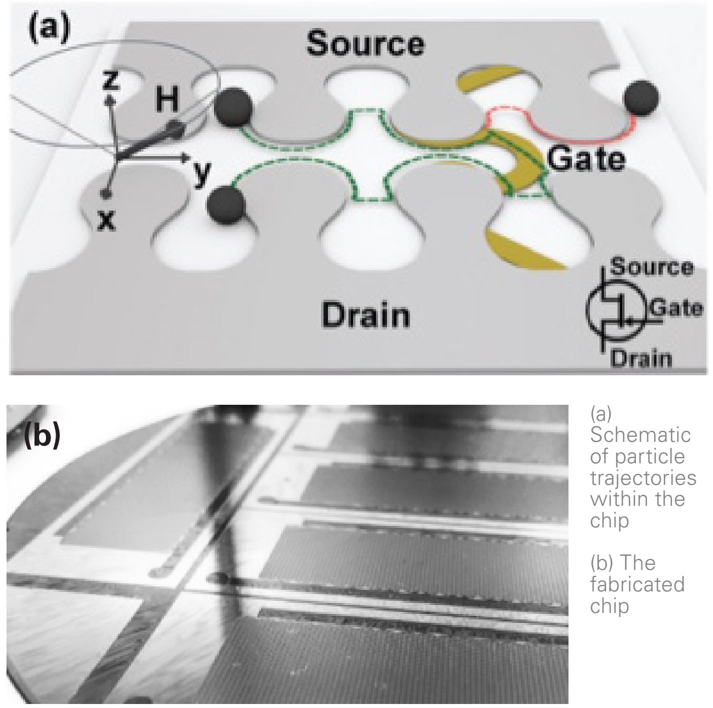


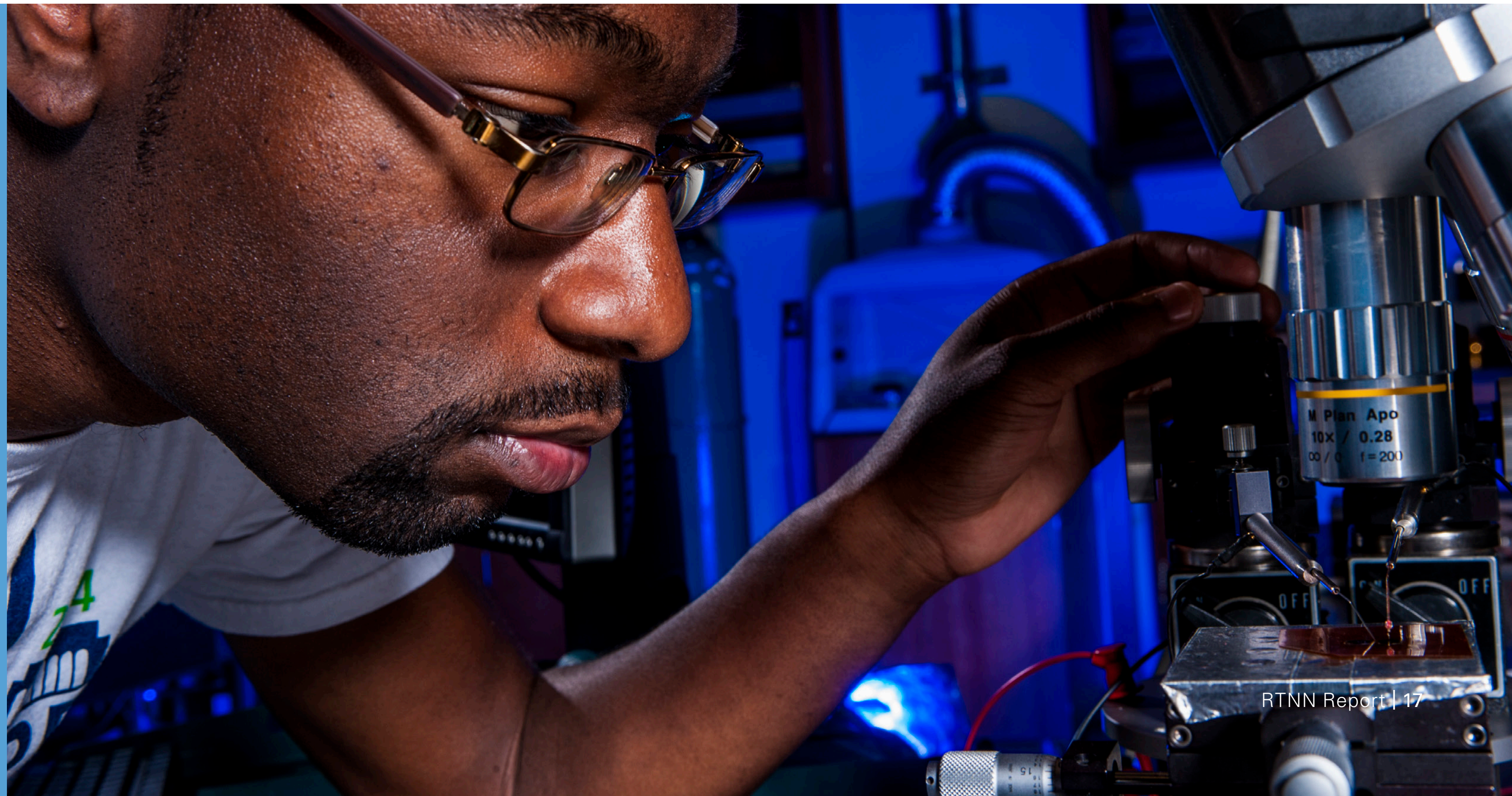
(a) Schematic of particle trajectories within the chip

(b) The fabricated chip

Collaborative Research Award

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 2017, Ugonna Ohiri was the recipient of this award for his project entitled “Programmable Self-Propulsion and Reconfiguration of Active Semiconductor Microparticles and Microdiodes.”

Ugonna is a graduate student in the lab of Dr. Nan Jokerst (Duke University, Department of Electrical and Computer Engineering). The work was performed in collaboration with Dr. C. Wyatt Shields and Koohee Han in the lab of Dr. Orlin Velev (NC State University, Department of Chemical and Biomolecular Engineering). They have demonstrated a new class of engineered semiconductor microparticles (and microdiodes) that draw energy from their environment to actively propel, rebound off of each other, and achieve on-demand sequential microparticle assembly and microparticle disassembly in a highly controllable fashion. In collaboration with Velev, the fabricated active Si microparticles and microdiodes have demonstrated powered interactions (repulsion, propulsion, and end-to-end attraction for chaining) in water. Depending on the AC frequency and electric field magnitude, these devices exhibit a myriad of interesting dynamics. The ability to electrically switch between two modes of dynamics — “active” powered motion and “reactive” attraction — is unique to their method and gives them an unprecedented ability to form and reconfigure functional structures.



OUTREACH HIGHLIGHTS

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

- **Knowledge** of the facilities' existence 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.

Nanotechnology, A Maker's Course

RTNN developed a free online course that gives an overview of nanotechnology tools and techniques and shows demonstrations 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 underlying science of a specific technique or instrument. The lectures make the information accessible to a large audience, using simple language and relatable analogies. In-lab demonstrations of the equipment follow each lecture with an explanation of each step in the process. The course launched in September 2017 and has more than 2,500 enrolled students. **coursera.org/learn/nanotechnology**

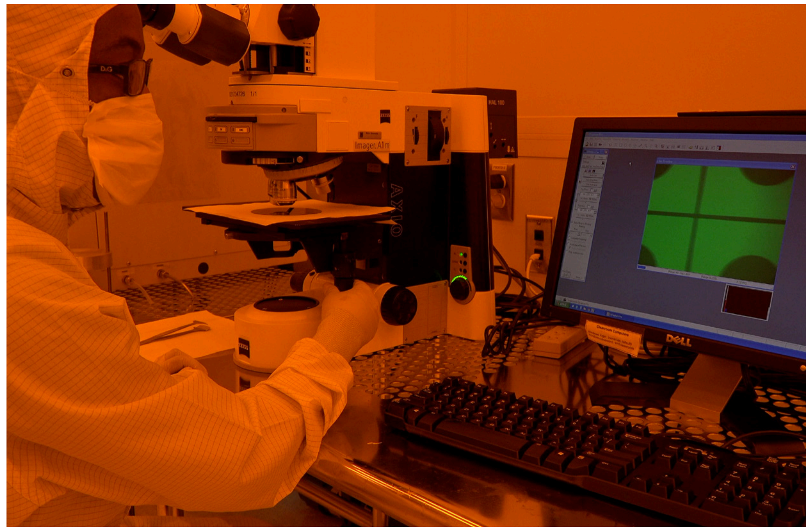
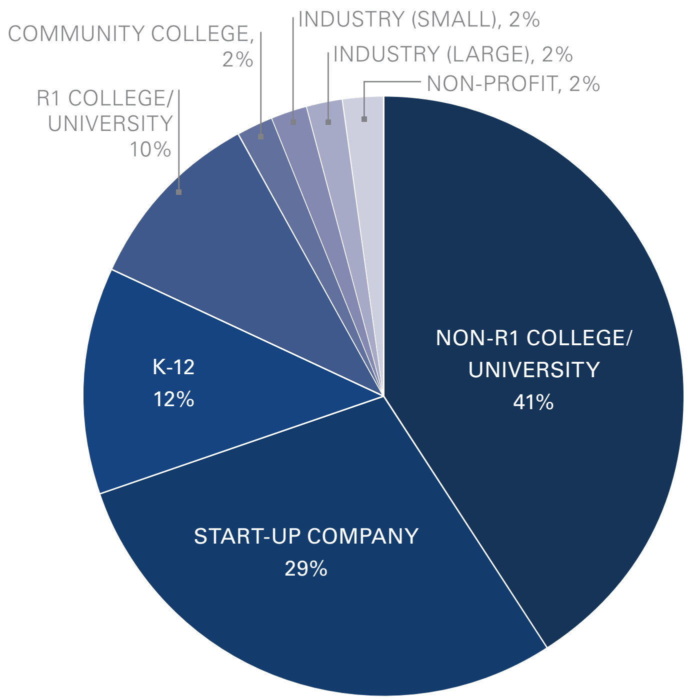


Image from *Nanotechnology, A Maker's Course.*

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 in RTNN member facilities. Proposed projects must be focused on research, preliminary development activity, or educational programming in an area of nano-scale science, engineering, and/or technology. More than 40 projects have been selected for the Kickstarter program, receiving greater than 800 hours in use. The majority of projects hail from non-R1 colleges/universities, start-ups, and K-12 students and classrooms. Many of the participants in this program have continued to use facilities with their own financial support. In addition, several participants have indicated that they are using data from their Kickstarter projects to support research proposals and include RTNN facility usage in these proposals.

KICKSTARTER USERS



Immersive lab experiences

The RTNN hosts many students throughout the year. This year more than 1,800 students visited our 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, scanning electron microscopy (SEM), photolithography, electromagnetism, and nanoparticle synthesis. Simple, one-page descriptions for teachers outline the program and how to get started. Each activity has its own document tailored to a specific age group (middle or high school).

Visits to classrooms

RTNN staff have also traveled to many K-12 classrooms and schools to introduce nanotechnology, interacting with more than 1,000 students. These visits are paired with hands-on activities. One of our exciting new additions this year is a portable, desktop SEM. This microscope makes it possible for us to take our facilities to the classroom. The desktop SEM is user-friendly and students can begin using it right away without complex and lengthy training sessions. The method for using the SEM is tailored for different activities and lengths of time. Students can collect samples for imaging ahead of time using provided sample collection kits. We can also use the SEM as a method to collect data for a research project. If time is limited, students can explore a set of RTNN-provided samples that includes different electronics, insects, and textiles.

K-12 lesson plans

This year, we developed four distinct lesson plans for K-12 educators. All of the lesson plans use RTNN facilities, remotely or on-site, in some capacity. They are targeted to different grade levels, focus on different fields of study and aspects of nanotechnology, and hit a variety of educational standards. The lesson plans are freely available to teachers on the RTNN website.

RTNN visitors gowned up to tour the clean room.

5th graders look at samples with the desktop SEM.

SEM image of an ant collected by students.

Science kits

The RTNN worked with Morehead Planetarium and Science Center to include a nanotechnology activity, “Sticky Sand,” into Science Night kits that were provided for free to 150 schools across the state. These kits enabled schools to host an evening event at their schools to promote science as a part of the North Carolina Science Festival. The kits included different science activities with instructions and supplies.

NC Science Festival

Each year, North Carolina reserves two weeks in April for the NC Science Festival. The NC Science Festival includes events across the state at K-12 schools, museums, universities, parks, etc. In 2017, 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. This year, due to high demand, there were two NanoDays with more than 250 students in attendance. During the festival, UNC opened its doors to the public to host a Science Expo. 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 festival. We took part in a number of these events by hosting RTNN booths with hands-on activities related to nanotechnology.

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 — via Skype, Google Hangouts, WebEx, etc. — 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. We have used this program to connect with classrooms using student provided samples. One of the Kickstarter projects included a laboratory class where students made chemical compounds and sent them to RTNN facilities for analysis. RTNN staff worked to analyze the samples, share their results with students, and assist them in the interpretation of their results.

SCIENCE KITS: BY THE NUMBERS

150 Events

31,540 Attendees

3,634 Staff

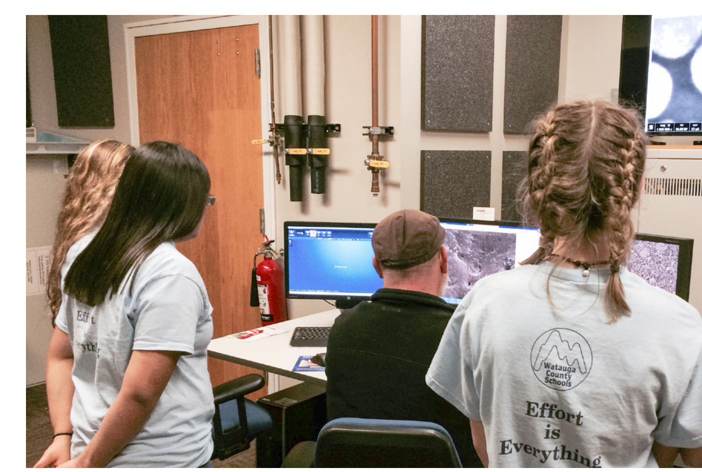
1,716 Volunteers

110 STEM Professionals

37,000 Total Participants

93 percent of schools that used the activity would recommend using it in future years

Learning about SEM at the Durham Public Library.



Middle school students watch a demonstration of the SEM during NanoDays.

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. This year, RTNN held 32 workshops and short courses with more than 140 participants.

Workshops for educators

The RTNN held a second two-day nanotechnology workshop for community college and small college educators in August 2017. The event exposed faculty members to nanotechnology and helped them to incorporate nanotechnology and the facilities into their community college curricula.

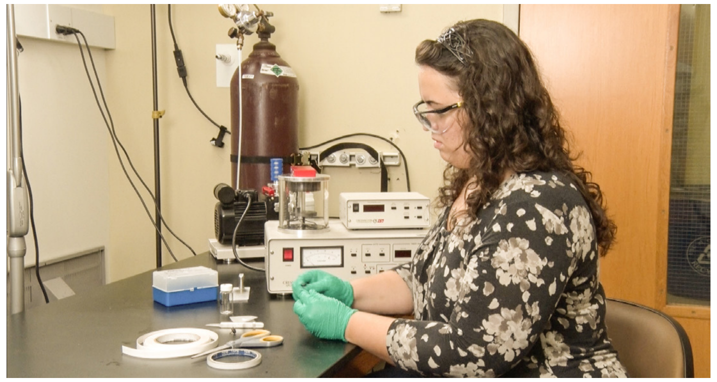
We have also held short workshops for local K-12 educators. These workshops inform educators of the numerous ways that they can interact with the facilities. During the event, educators get a tour of the facilities and demonstrations to give them a better sense of what is possible. Educators receive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

OUTREACH NUMBERS

- **More than 3,000 people reached in year two**
- **More than 60 percent participation by underrepresented groups in STEM**

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. Brienne Johnson (NC State), Catherine McKenas (UNC), and Morgan Irons (Duke) were the 2017 recipients of this award.



Catherine McKenas

Morgan Irons

Brienne Johnson

NANOTECHNOLOGY LEADERSHIP IN THE TRIANGLE

The RTNN works with other community organizations to promote nanotechnology in the Triangle. We work with NC COIN to connect industry users with nanotechnology tools and expertise. We have partnered with Morehead to distribute nanotechnology educational activities to K-12 schools across the state. We are engaged with NCNGN to strengthen our ability to reach the public in libraries and community centers through remote access of our facilities.

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 organized a series of luncheon discussions to enable scientists in nanotechnology and water to meet one another, interact, and brainstorm ideas for innovative, collaborative projects. The group prepared a proposal for NC State's Game-Changing Research Incentive Program (GRIP). The group received the $575k award in December 2016 and began work immediately. In March 2017, the team hosted a symposium on water sustainability through nanotechnology at the Water Resources Research Institute annual meeting. Two invited external researchers gave keynote talks: Dr. Qilin Li (Rice University's Nano-enabled Water Technologies, NEWT ERC) and Dr. Matias Vanotti (USDA's Agricultural Research Service). Project leads also presented their research plans and preliminary results.

We actively seek out opportunities to strengthen and broaden our capabilities including proposals for: Research Experience for Teachers; Advancing Informal Stem Learning; Innovations at the Nexus of Food, Water, and Energy Systems (INFEWS); and Major Research Instrumentation at all three institutions.

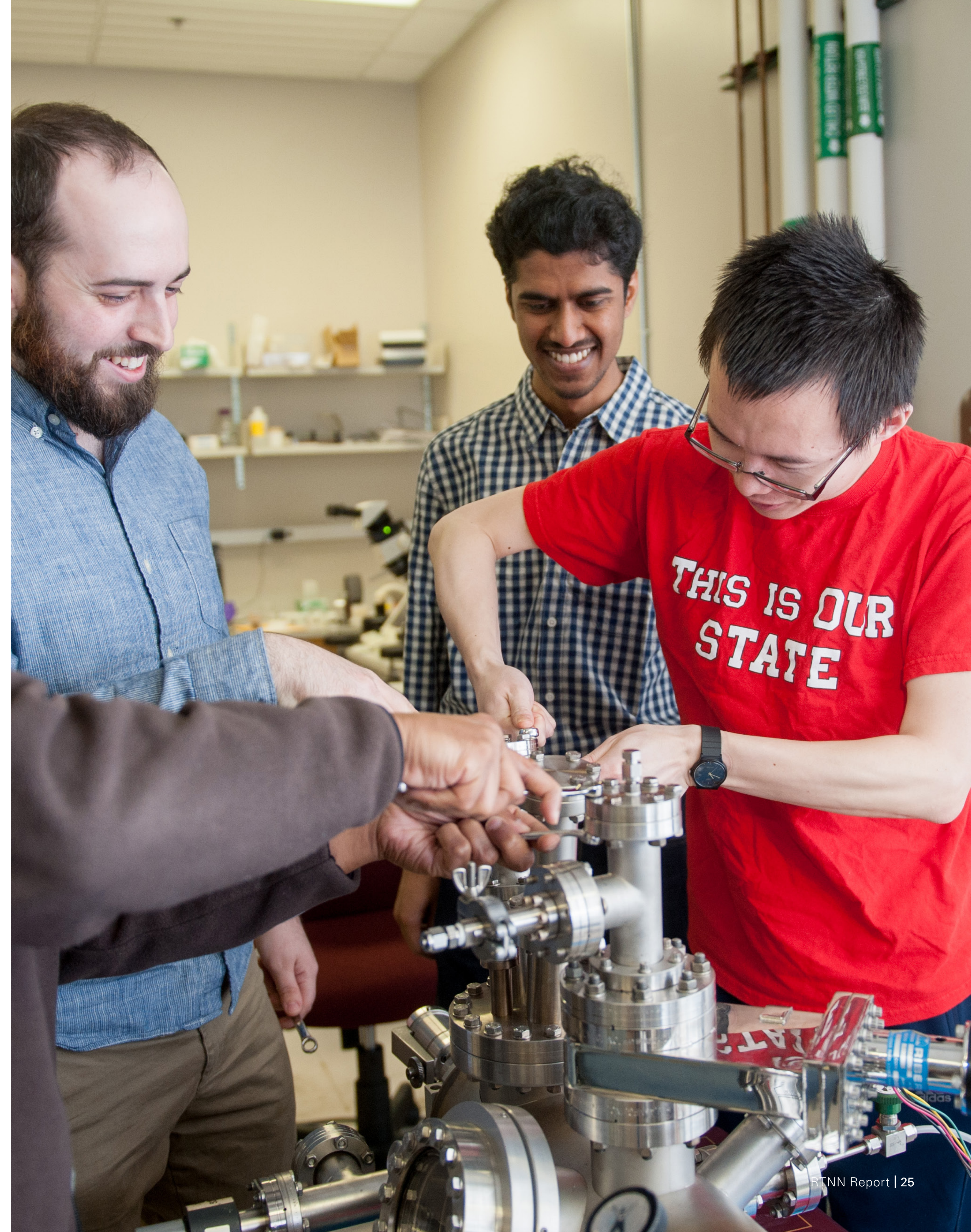
In November, the RTNN organized nanotechnology faculty members to talk at the monthly RTP180 event held in Research Triangle Park. RTP180 is held at The Frontier and features speakers from Triangle universities, local companies, and the community at-large who take the stage to speak passionately about what matters to them. Daphne Klotsa (UNC), Claudia Gunsch (Duke), and Tori Miller (NC State) related their work in nano to a packed house. Dr. Klotsa kicked off the evening, highlighting her work in modeling nanoparticle packing. Dr. Gunsch emphasized the importance of studying the unintended effects of silver nanoparticles in the environment. Dr. Miller closed the evening talks, giving an overview of her work in metallurgy.

COIN

The North Carolina Center of Innovation Network

NC NGN NORTH CAROLINA NEXT GENERATION NETWORK

WATER SUSTAINABILITY THROUGH NANOTECHNOLOGY



NATIONAL IMPACT AND ENGAGEMENT

In honor of National Nanotechnology Day, the RTNN hosted "Small Talk: a NanoMaker Live Event" on October 10th. Experts answered questions on nano-fabrication and characterization. The event was streamed online during two, hour-long sessions. Questions could be submitted online prior to the event or live via social media. Those who tuned in learned how to wash clean room gowns and why the Nobel Prize was awarded for cryo-EM.

The RTNN is actively involved in NNCI working groups and committees

- Chair of the Building the User Base Subcommittee
- Key member of Diversity Subcommittee
- Membership in Education and Outreach, Workforce Training, Online Technical Learning, Environmental Health and Safety, and XPS working groups

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

Our staff attend diverse national conferences to raise awareness of RTNN and NNCI programs and technical capabilities.

We have partnered with the RAIN network to bring our remote access capabilities to a national stage.

The RTNN is also growing internationally. Last summer we hosted a Japanese student from the National Institute of Materials Science (NIMS) in Japan. *Nanotechnology: A Maker's Course* also draws learners from around the world.

GLOBAL REACH

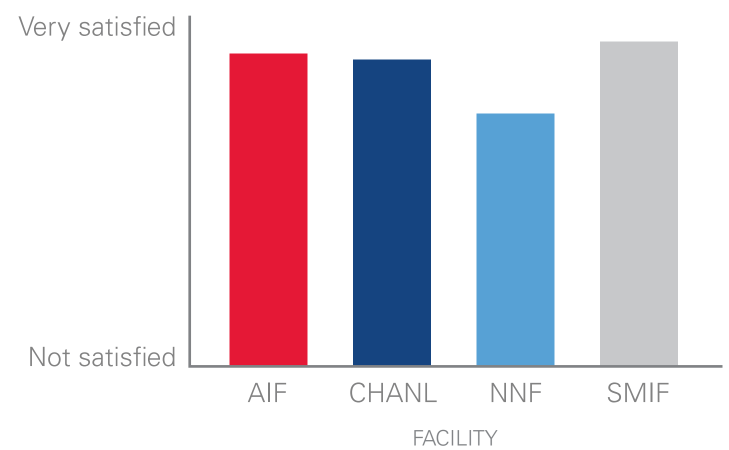
RTNN impacts people across the world from learners in our Nanomakers course to contributing authors on peer-reviewed publications.

NANOTECHNOLOGY OUTCOMES

RTNN user satisfaction and programming are assessed regularly to identify real issues and effect change.

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. Greater than 98 percent of users indicated that they would return to the lab if further work was necessary. One of the facilities had a lower average satisfaction score compared to the other facilities. This information was used to guide a restructuring of the facility.



Kickstarter program feedback

To assess the Kickstarter program, semi-structured interviews were conducted with 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 and awe of RTNN staff. Many staff members were thanked by name by the program participants.

"...she was extremely helpful...They were very good at getting back to me...you don't normally see that in dealing with companies..."

Outreach feedback

Many of our facility tours are given to students under the age of 18. As a result, we assess these tours by sending the surveys to teachers, camp counselors, and/or school group leaders. Data was collected from July 2016 – March 2017. During this time period, more than 1,000 students visited RTNN facilities.

When asked on their likelihood to return or refer others to RTNN for a tour, greater than 95 percent of respondents noted that they were very likely or likely to return or recommend.

OUTCOME NUMBERS

» **$73.5 million in research activity, as defined by annual research expenditures, for projects that utilized the facilities**

» **83 Graduate degrees**

» **15 Patents issued**

» **26 Patents filed**

GETTING STARTED WITH RTNN

Contact the RTNN to connect you with expert technical staff and faculty members to provide:

- Training for users 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.

Jacob Jones
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Nan Jokerst
Duke Site Director, nan.jokerst@duke.edu
Jim Cahoon
UNC-CH Site Director, jfcahoon@unc.edu
David Berube
SEIN and Assessment Coordinator, dmberube@ncsu.edu

Core Facilities and Centers

Dedicated Characterization Facilities

- Analytical Instrumentation Facility (AIF), NC State
- Center for the Environmental Implications of Nanotechnology (CEINT), Duke
- Duke Magnetic Resonance Spectroscopy Center (DMRSC), Duke
- PULSTAR Reactor, NC State
- Chemical Analysis and Spectroscopy Lab (CASL), NC State

Fabrication, Processing, and Characterization Facilities

- Chapel Hill Analytical and Nanofabrication Laboratory (CHANL), UNC-CH
- NC State Nanofabrication Facility (NNF), NC State
- Shared Materials Instrumentation Facility (SMIF), Duke
- Zeis Textiles Extension (ZTE), NC State

International Partner Facilities

- Environmental Flow Research Centre (EnFlo), University of Surrey
- European Centre of Research and Teaching of Geosciences of the Environment (CEREGE), Aix-Marseille University

SEIN Center

- Public Communication of Science and Technology Project (PCOST), NC State

CHECK OUT **RTNN**

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