The Move-In Edition

NanoteQ is a research center of Wake Forest University established as a resource for the development of emerging *Frontier Technologies*.

NANOTEQ
Nano/Quantum Technologies Laboratory

NanoteQNews
Volume 2 Iss. 2
Summer/Fall

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NanoteQNews (NN) is a service of NanoteQ (N/QTL) at Wake Forest University. It is produced four times a year and back issues are available at the NanoteQ website (www.wake-nanotech.org). The opinions and commentary expressed herein are those of the writers and the editor of NanoteQNews (NN) and do not reflect official positions of WFU or its affiliates. The individual editors of NN maintain full editorial rights over the materials presented in the newsletter.

The Newton Apple Project

The Faculty, Students and Staff of NanoteQ recently undertook the germination and husbandry of seeds from the Flower of Kent apple trees from the actual estate of Sir Issac Newton. Known as the ***Newton Apple Project***, our interest stems from the common story that Sir Issac Newton came up with the theory of gravity by watching an apple fall to the ground in his back garden. If this is true, then that apple would have fallen from a tree that was a direct ancestor of the seedlings we are growing at NanoteQ. However, these are the "children" of that plant. Apples are heterozygous, which means that each apple will have various sets of dominant and recessive genes. And since apple trees must be cross pollinated to fruit, one gets a totally unique mix of genetics in the "children." Nevertheless, the "mommy tree" of the NanoteQ seedlings came from a direct clone of the tree that Newton would have watched, if indeed he watched anything at all. Each student, faculty postdoc, etc. at NanoteQ is growing their trees so that they may be replanted across our campus thereby establishing this species throughout the city of Winston.

Cleanroom Madness

The *NanoFabrik* Team at NanoteQ is a group of scientist and engineers that volunteer their time to design the capabilities and facilities that NanoteQ needs to do its work. This important contribution of time and expertise allows NanoteQ to stay competitive in capabilities without the extraordinary budgets of facilities such as those at Stanford or MIT. The willingness of people to step up and help for the good of Wake has always been Wake's strongest asset and the NanoteQ Lab is one of those examples of this unique aspect of the school's community.

This time *NanoFabrik* has developed a cleanroom facility at Wake that is absolutely superb. The WFU cleanrooms are actually three separate cleanroom "bays." The first bay is a simple ISO 7 Class 10,000 cleanroom environment that is built for packaging and chip post processing. The second bay is ISO 6 or class 1000. Finally, the ISO 5 class 100 processing bay is for the creation of nanoscale integrated Si-based devices.

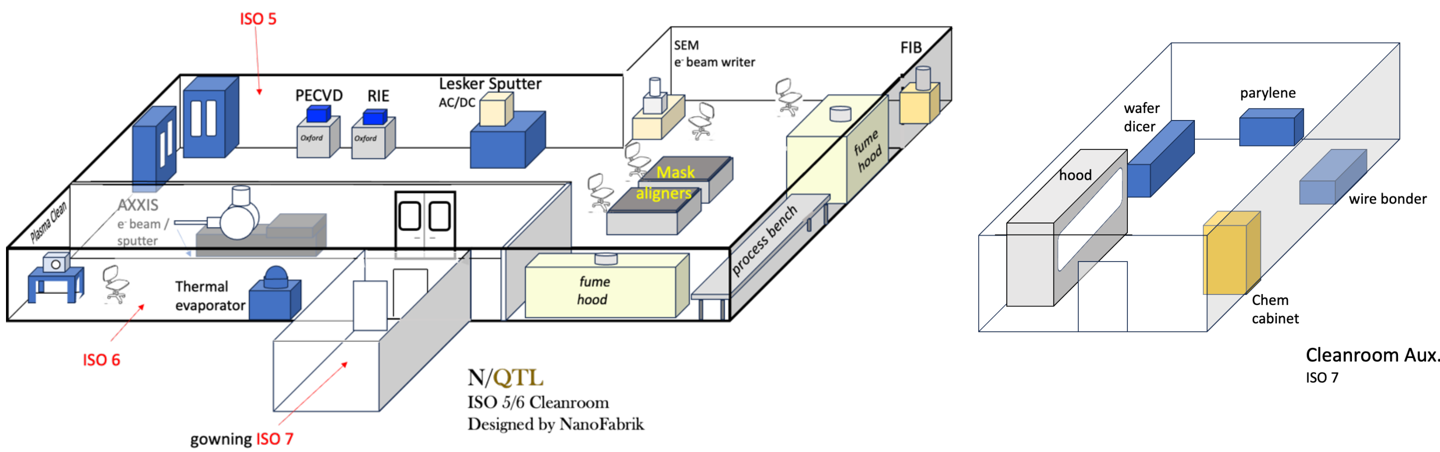
ISO Class Number		Maximum allowable concentrations (particles/m3) for particles equal to and greater than the considered size					
		0.1 µm	0.2 µm	0.3 µm	0.5 µm	1 µm	5 µm
Cleanest	1	10					
	2	100	24	10			
	3	1,000	237	102	35		
	4	10,000	2,370	1,020	352	83	
(Class 100)	5	100,000	23,700	10,200	3,520	832	
(Class 1,000)	6	1,000,000	237,000	102,000	35,200	8,320	293
(Class 10,000)	7				352,000	83,200	2,930
(Class 100,000)	8				3,520,000	832,000	29,300
	9				35,200,000	8,320,000	293,000

ISO CLEANROOM

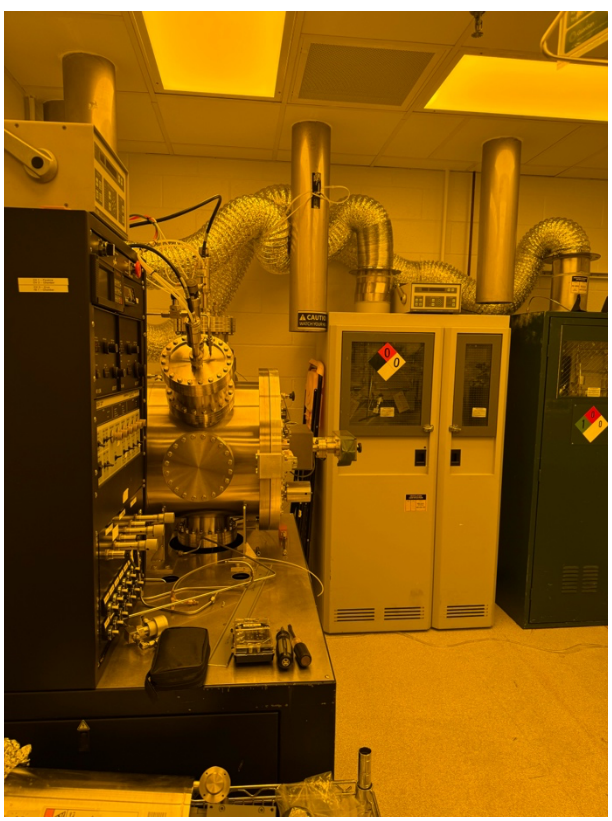
ISO14644-1:2015 Table 1
(Fed-Std-209E)

While class 1000 and class 10,000 (ISO 6 and 7) are relatively easy to design and can be easily managed, the ISO 5 - a class 100 cleanroom - is far more challenging. To get to this rating, air velocities within the room must achieve specific values and must follow specific patterns. Moreover, the air must be much cleaner than ISO 6 with an increased demand of > 10 air replacements per minute. To achieve this NanoFabrik coupled FEA calculations of the room with staged equipment placements, and small physical models to test new ideas. By creating a system of laminar air-flow zones, the team was able to create the conditions of ISO 5 using a virtual lower and side plenum configuration hybridized with sets of spot-located air scrubbers, blowers, and internal air dryers. SimScale air velocity maps were then used to understand how random motion in a 2 person, 3 person, and 4 person occupancy within the room might disrupt airflow and lead to enhanced contamination. The room was built to account for such variations by using an active management system in which five separate sensors throughout the room measure particle counts, VOC's, Temp and RH, as well as air velocities and are used to feedback info continuously and manage internal airflow.

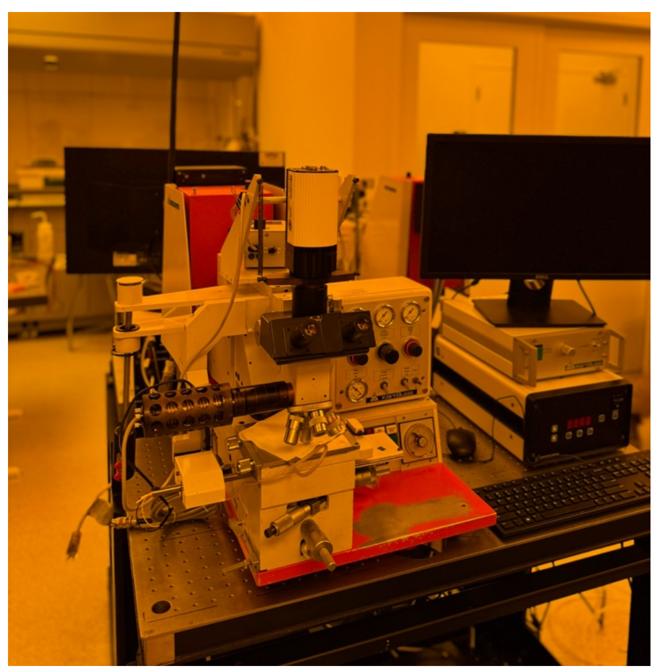
An additional aspect of this environmental management system is the ***Gas Handling System*** designed specifically for the WFU cleanroom. The gas cabinets are from Bosch, and manifolds are built by a specialty company in California. This system handles the dangerous volatiles associated with the RIE and PECVD processes.

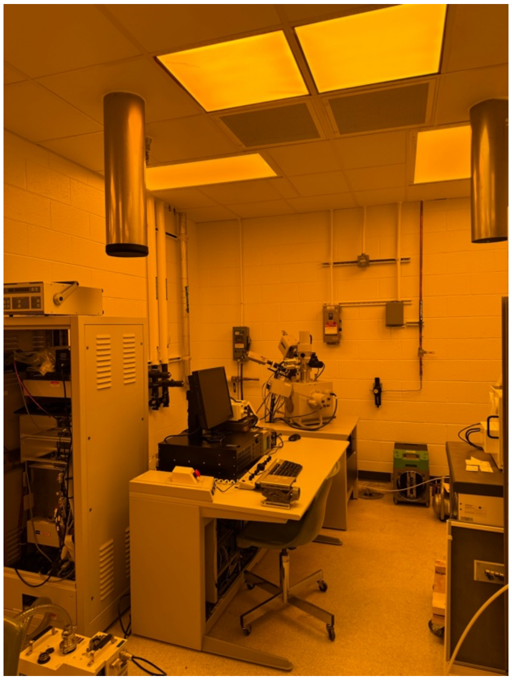


The layout of the cleanrooms at NanoteQ are shown above. The total space of the cleanrooms is about 1500 sq. ft. of operational space and an additional 1500 sq. ft. in mechanical room that is located above the workspace.



Here the gas handling system as well as the AXISS ebeam, focused ion beam system can be seem. Below is show two of the three specialized mask aligners in the cleanroom.





The FEI FIB 400M and Zeiss Supera 25 NPGS ebeam lithography system are still being installed in the cleanroom, but this should be done very soon. The addition of these tools together with the array of plasma processing and deposition systems NanoteQ has NEMS and circuit resolutions of around 10 nm in Si and SiN_x systems.

The WFU facility is a very small, but extremely well equipped and capable cleanroom facility. NanoFabrik has shown that this novel design is only viable for such small environments. But the WFU cleanroom achieves class 100 standards and its operational costs are significantly lower per square foot as compared to other ISO 5 facilities with the same capabilities. Estimated operational costs for the Wake Cleanroom is approximately \$33,000/year. An average cost for the facilities* at Duke, Vanderbilt, Miami, Dartmouth, is roughly double this at ~\$70,000/year for the same sq. ft. (* part of the comparison overlap group that we use to monitor our costs and capabilities. These are "all-in" costs excluding manpower so that they may be directly compared)

We note that at WFU funding for the cleanroom comes entirely from the indirect generated by Prof. Carroll's research grants and gifts from our donors. No user pays for access to the cleanroom and we are the only facility in the U.S. (to our knowledge) that does this. For 24/25 the facility has 5 users: 3 internal and 2 external (associated with grants) with approximately one enquiry per month from potential external users. We cannot currently accommodate such requests leading to an estimated loss of roughly \$3000/month in external user fees that could cover the operations of this facility and establish funding for equipment renewal. NanoteQ has requested permission to establish a recharge center for more than 20 years as was agreed under our MOU with the university. To date this MOU and its agreements is not a priority for WFU.

Microscopy Under a Microscope…

The first facility, and the most heavily used at NanoteQ is the microscopy facility. Over the course of a year, we will have between 25 to 35 users of our microscopes from across WFU campuses and from the larger statewide research community. None of these users will be charged for access yielding an estimated loss of roughly \$6000/month in user fees that could be applied to operations. The same funding model as above is applied to microscopy. NanoteQ has requested permission to establish a recharge center for more than 20 years as was agreed under our MOU with the university. To date this MOU and its agreements is not a priority for WFU.

Is our facility competitive with a Gen 3 + machine?

Microscopy facilities can be categorized by the resolving power that they offer (equipment) and how they offer it (access). The most powerful and newest generation of C_s - corrected microscopes (Gen 4) and double aberration corrected, omega filtered systems (Gen 4+) are extremely expensive to purchase, and to keep running. They are found in the most expensive, largest user base, electron microscopy facilities. Normally such facilities must receive a supplemental budget from the university or organization as well as charging a significant user fee from a large user base (usually around 30 – 50 users minimum) to sustain its operation. Across the U.S. there are ~ 15 (round numbers) such super facilities including the likes of Stanford, Berkeley, MIT, Cornell, Oak Ridge, and so on. These centers offer superior analytical imaging at world-beating resolutions. But they also offer a range of auxiliary imaging, sample preparation, and expertise in imaging that most facilities do not have. Remember the machine is only ½ of what makes a great facility, the support is the other half. Thus, they go further than just buying the machine and plugging it in.

Of course, there are numerous universities that also have such Gen. 4 machines but they lack a large user base, a technical staff, or auxiliary sample prep and support to fully utilize such machines. They cannot really be said to operate a "user facility" in the sense of the above. They do have a capability, but they rarely realize its potential. This is best exemplified by a "local facility" that recently reduced its materials imaging/analysis capabilities in favor of a machine that had more bio-capabilities and was cheaper to operate. This was a function of costs not priorities. The cost of operation was high and the reduced life cycle of such machines (they are very expensive to repair and so they get replaced more often than Gen 3 systems) made it essentially impossible to continue with that capability set. The second example is a little further away at a "well-known and very well-funded small university" with a Gen 4 setup. In their case nearly all recent publications requiring true HRTEM have come from their collaboration with ORNL and not home based at all! Indeed, by their own numbers the loss of this machine would have likely have not impacted publication numbers at all.

National Level Facilities	Gen of Microscope	Breadth of imaging	Aux. Sample Lab	
ORNL	Gen 4+	5	5	These are nationally and internationally recognized powerhouses of electron imaging. Multiple machines of the best possible kinds.
Argonne	Gen 4+	5	5	
Berkeley	Gen 4+	5	5	
Stanford	Gen 4+	5	5	
Cornell	Gen 4	5	5	
MIT/Harvard	Gen 4	5	5	
Northwestern	Gen 4	5	5	
UC Irvine	Gen 4	5	5	
U. Chicago	Gen 4	5	5	
U Illinois UC	Gen 4	5	5	
Lehigh U.	Gen 4	5	5	
U Penn	Gen 4	5	5	
CalTech	Gen 4	5	5	
National Level Capabilities				
Rice U.	Gen 4	4	3	These institutions have top of the line instruments, but they generally have only a single important machine with little else.
UT Dallas	Gen 4	4	3	
VaTech	Gen 4	3	3	
GaTech	Gen 4 -	3	3	
FSU/NHMFL	Gen 4	3	3	
U Texas Austin	Gen 4 -	3	3	
Dartmouth	Gen 4 -	3	3	
Columbia	Gen 4 -	3	3	
Regional Facilities				
U Tenn	Gen 3	2	2	These facilities are designed to fulfill the needs of ongoing research. They have broadly based capabilities, multiple imaging modalities and so on.
Wake Forest	Gen 3 +	4	4	
Duke	Gen 3 +	2	3	
UNC	Gen 3	2	3	
Clemson	Gen 3	2	2	
UGA	Gen 3	2	2	
UF	Gen 3	2	2	
Vanderbilt	Gen 3+	2	2	
NCSU	Gen 4 -	3 +	3	
Johns Hopkins	Gen 3 +	2	3	
Regional Level Capabilities				
Miami	Gen 3	2	2	These facilities are at the average of most institutions across the country. UArk, ULa, Ole Miss, SMU, U. S.Car. etc.
UVa	Gen 3	2	2	
BC	Gen 3	2	2	
Tufts	Gen 3	2	2	
Emory	Gen 3 -	1	2	
…				

Currently, there are four significant microscopy facilities in North Carolina: Duke, UNC, NCSU and Wake. These four universities provide access to microscopes + auxiliary equipment and capabilities to allow for publishable imaging. (JSNN, App State, and UNC Charlotte have microscopes but generally do not operate imaging facilities. Their machines are dedicated to specific tasks for a few faculty). The Duke, UNC, NCSU, and Wake facilities utilize topflight Gen 3+ microscopes with NCSU offering some analytical services from a Gen 4. Of these NCSU and Wake have built imaging centers around multiple user groups with a broad range of imaging machines, analytical capabilities, and sample prep systems with enough users to make sure that systems are constantly upgraded and capable. These are very good imaging centers and while they operate on relatively small budgets we note that a majority of research universities in the U.S. have no access to Gen 4 systems or well supported Gen 3/Gen 3+ instruments, offering instead only reduced resolution, partial training and support and limited analytical capabilities, with no significant complimentary imaging.

So, what is the state of our microscopy facility after the move?

As judged by the equipment it has (its resolution and capabilities) and the expertise it arrays around this equipment, Wake Forest University NanoteQ is quite a good facility on a regional scale. However, it is not yet a nationally competitive facility. From the table above, when compared with our regional research overlaps Wake does very well. It is significantly better than most regional imaging facilities. To provide for the capabilities we lack, we have teamed with NCSU and ORNL for aberration correction access when needed. This enhances our overall impact. It is our goal to see WFU eventually step up to the national level since these capabilities are the backbone of working at the nanoscale.

Wake Forest operates six electron microscopes, two TEMs and three SEMs in the imaging center, one SEM in the cleanroom. The cleanroom system is an ebeam writer with NPGS.

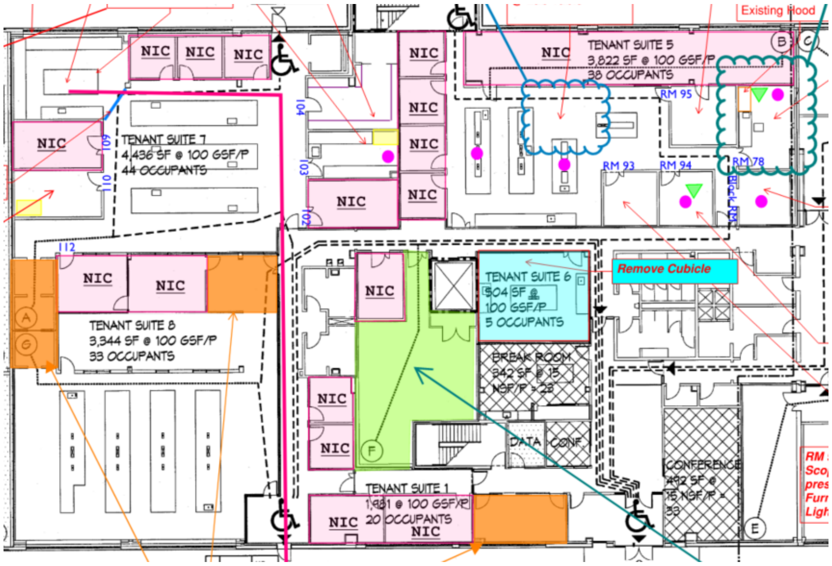
The imaging facility also offers a RHK UHV VT-STM, a JEOL SPM 5200, and a Bruker Dimension 3100. These scanning probes are regularly maintenance, equipped with several scanning probe modes such as LFM, MFM, EFM, and more. The 5200 offers a cold stage for LN_2 and a vacuum of 10^{-6} Torr, The RHK STM has a flow LHe cryostat and 10^{-11} Torr vacuum. It is designed for high resolution spectroscopy.

Finally, the facility has a broad range of analytical capabilities. These include electron energy loss spectroscopy (EELS) from a Gatan imaging filter (GIF) system, Energy Dispersive Analytical X-ray (EDAX) from an Oxford INCA system available both on our SEMs and TEMs. X-ray photoelectron spectroscopy as well as Auger Spectroscopy is available from a RBS refurbished PHI system.

WFU microscopy has an ongoing relationship with EM control for the maintenance and regular refurbishment of the microscopes. Recently the JEM 6340F was replaced by a Hitachi S4700 (also a field emission machine) the Hitachi 2000 was replaced by a Hitachi S3000N with EDS and ambient chamber, the JEM 6330F was installed, the JEOL 1200 EX was refurbished with a column rebuilt, new goniometer, and new projection lens. The HRTEM 2010F is still undergoing refurb, with new lens power supplies for lower noise, new apertures, a rebuilt of the electronic FASTem system, reconditioning of the gun, replacement of several control boards and an overall cleaning and polishing of all internal connectors. We expect it to be up and running again shortly, but as it enters service again it will be significantly more capable than it was when it was new, with lower noise profiles, better stability, and atomic resolution even when using its VT stages.

The Dimension 3100 was installed by AFM services inc. out of Santa Barbara, and the JEOL 5200 was the first of our microscopes to go online after the move. The XPS system is still undergoing refurb. New water chillers have been added for all systems, new pumps and air compressors have been added in many cases. Environmental and sound control – especially for the 2010F has been an important new addition.

The Building



The building at 95 W 32 Street, NanoteQ's new home, is particularly well suited for the microscopy center. While the building wasn't necessarily designed specifically for HR microscopes, the unusually thick slab foundations of the building, the well shielded mechanical room that takes up the whole second floor of the building, multiple water supplies, including house chilled water, air compressors and other utilities that are remoted, could not have been better designed. The University, together with EM Control, and NanoFabrik, did the rest to build this facility into something with the potential to grow. With a little care and support from WFU as well as our donors, WFU imaging facility has established the roots it needs to become the premier academic imaging center in the southeast.

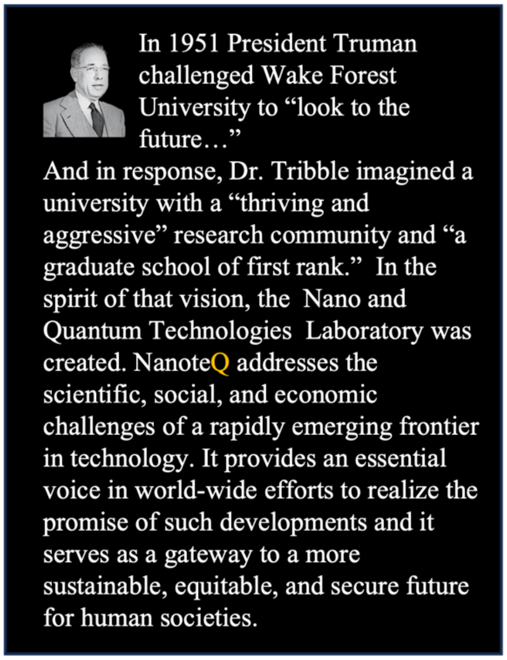
Data

For 24/25 we have undergone a major disruption in operations so for the first 6 months of the year we have been moving. During this year we have implemented a new user tracking system called "labshake." (https://labshake.com) This is an online scheduling software package that lists all our equipment, allows reservations and keeps track of your hours. It can also generate billing when necessary and is compliant with the reporting and accounting necessary for the establishment of a recharge center.

The 24/25 numbers:

- 35% of available time on all microscopes was used. This reflects the reduced staff time due to the move.
- Most used instruments were the 4700 and the 1200 EX with the 3000N and the 5200 next.
- 50% of users were from the medical school.
- 35% of users were external to the University.
- All major external users had grants to do their work.
- ½ of all use needed tech support.
- The facility supplied new training to 10 people.
- Major papers self-reported from the facility: 5 (we note that medical school and external users rarely respond to our use surveys)

Donors



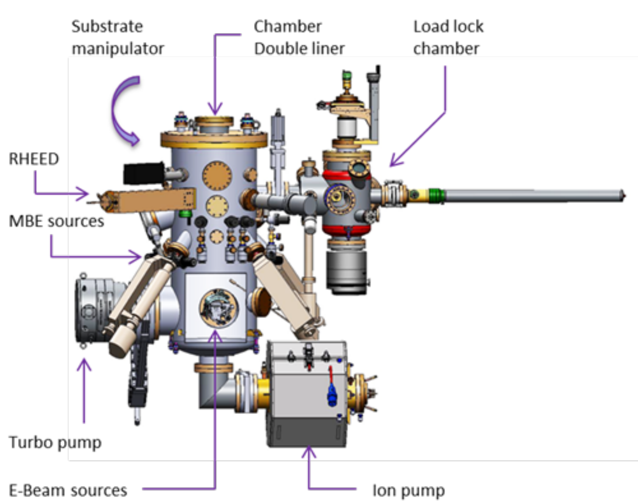
Many people do not realize that NanoteQ receives between 100K and 250K per year in donations of equipment, and funding (in the form of purchases). This year we added several new donors to our list (see www.wake-nanotech.org for a list). The Laboratory received two major donations of operational Raman Systems an Almega Raman microscope from ThermoFisher and a Jobin-Yvon Horiba T64000 triple spectrometer confocal Raman system. These systems have significantly enhanced our analytical capabilities and are currently being installed and calibrated.

But this is not all. There are several other significant donations to the lab this year which will allow for new materials growth capabilities, low temperature transport capabilities, and new HTC superconductor processing that we were previously unable to do.

NanoteQ and WFU appreciates the forward-looking confidence and faith of our donors and the impact that they make every day to our students and our scholarship.

The donors sign that is placed just outside the cleanroom entrance restating the vision originally put forward for Wake Forest University as it moved to Winston Salem from its original home.

Growing New Materials With MBE



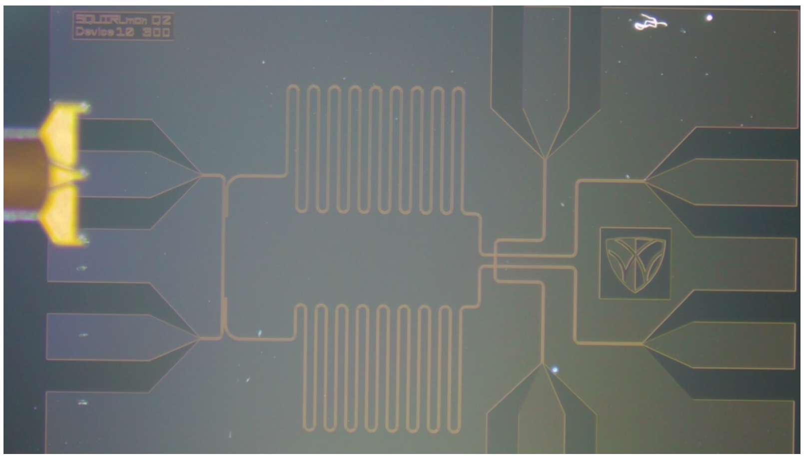
An exciting new dimension has been added to NanoteQ during the move. Thanks to donors we are now building an amazing new Molecular Beam Epitaxy (MBE) capability. This system, located in the main NanoteQ shared lab, is of standard RIBER design and is equipped with four programmable RIBER Knudsen Cells, a Cracker cell, a cryo-shroud for ultra-low vacuum depositions, a prep chamber for substrate cleaning, and a variety of analytical tools for use during growth. While we anticipate the system to be ready by December, there will be some time to calibrate its components and begin growth of materials. The cells will be initially setup for the growth and study of a variety of chalcogenide superlattices in support of the work being done in topological materials.

MBE allows the growth of thin films of tailored composition by creating the environment in which atomic layers arrive at the support substrate in ratios and at rates that lets us create new substances, highly doped versions of known substances, and layered architectures of substances in a pristine and purely crystalline form. It is a power way of controlling multilayered architectures of 2D materials.

And the Rest of the Lab…

Of course, the chemistry lab, the optics lab, and the organics lab are still being assembled and calibrated. In each of these cases, students and staff have pulled together to get NanoteQ back up and running as quickly as possible, but it does take time. Moving cause some significant damage to equipment, and rotovaps, ultracentrifuges, alpha steppers, etc. have all had to be replaced or repaired. However, we note that this is in line with the experience of other labs that have moved and so wasn't unexpected.

A Thaw in Qubits



A Dual-Rail HT qubit built in WFU's cleanrooms: Image courtesy of Tim Carlson (NanoteQ)

In most quantum computing technologies, qubits such as IBM's transmons or Google's majorana braiding systems must be held at extraordinarily cold temperatures. This requirement comes from several directions in quantum tech, for example, the energy level spacing of the quantum system that holds the information, the superconducting co-planar waveguides used as part of the qubit, or to "talk" to the qubit (depending on the design), the needed reduction of environmental noise during read-out phases of logical processes, etc. But working at 5 mK to 20 mK is costly and challenging and so it has long been desired to raise the operational temperatures of such devices.

Linked in some way with this temperature requirement is the error rates that quantum systems express inherently. For *w*QED (circuit based) qubits like transmons, photon loss within the qubit leads to *erasure error*, the largest source of error for the qubit. To combat this situation, the group at Yale [https://arxiv.org/pdf/2307.03169] came up with a clever way of linking two qubits together forming a resonance between them for the photons that they use to entangle. This makes the loss of a photon extremely easy to detect and so the error in the qubit can be corrected quickly. These are known as Dual-Rail qubits and they are the name-of-the-game in today's qubit landscape.

Researchers at NanoteQ have been working for some time on a version of a qubit that is based on topological insulators with much larger energy level spacings. This makes them a potential high temperature qubit system. These topological systems operate in the high GHz – THz energy region which means they too suffer from photon loss. But at temperatures near 25 ^{o}C, the heat bath makes these error much worse. Recently the WFU team has achieved a promising new milestone in their development. They have announced their first high temperature, THz, dual-rail qubit based on 2D topological insulators. This system is shown here, but not the details. For these you must wait for their upcoming publication.

N/QTL business

A new **Operating Board** is named this year. (the board only serves for two years and this is the second year of the current class. The **Advisory Board**, composed of business and community leaders, legal experts, and outside academics will also be named this year. If you have nominations please let us know.

NanoteQNews is produced quarterly and serves to update the WFU community of activities and opportunities of NanoteQ. NanoteQ is a research center of WFU and is open to all its campuses. If you wish to be removed from mailing lists or have news to share with the research community, please let us know at carroldl@wfu.edu