Quantum NanoFab Core Facility

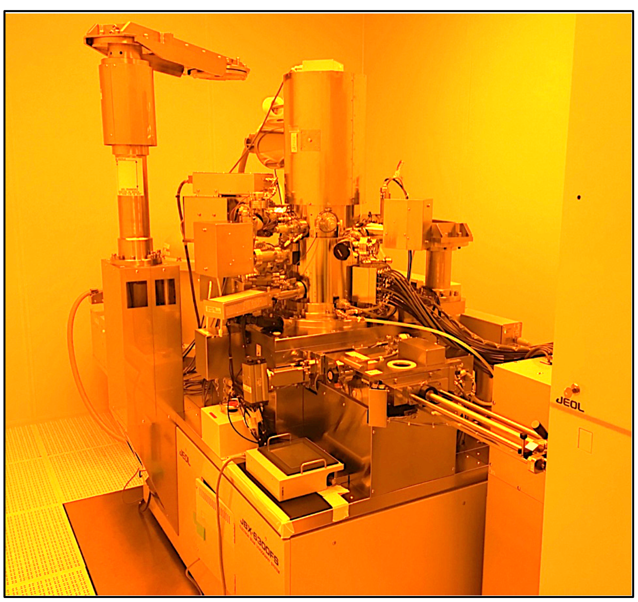
Annual Report

2015/16

Covering period May 1, 2015 to April 30, 2016

Vito Logiudice

12/9/2016



Cleanroom module 1701M housing newly commissioned 100kV JEOL JBX-6300FS Direct Write E-Beam Lithography System

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Students peering into Quantum NanoFab from ground floor atrium

The Quantum NanoFab is a popular stop for campus tours

SPECIAL THANKS

We remain deeply indebted to:

Mike and Ophelia Lazaridis

The University of Waterloo

Canada Foundation for Innovation

Ontario Ministry of Economic Development and Innovation

Industry Canada

We are grateful to **Ian Orchard, Vice-President Academic & Provost**, for covering the facility's substantial nitrogen consumption costs.

We are grateful to **Scott Nicoll, Manager, Space Planning**, and **Beth Jewkes, Associate Provost, Resources**, for having managed the bulk nitrogen supply for the entire Lazaridis Quantum-Nano Centre complex since the start of QNC operations, and for carrying these substantial costs for the first two years of operations.

We are grateful to **Raymond Laflamme, Executive Director, IQC** and **IQC** for funding a significant portion of Quantum NanoFab operations since 2009, and for funding the acquisition of a state of the art 100kV electron beam lithography (EBL) system.

Special thanks to **Rick Zalagenas, Director, Maintenance & Utilities**, **Chris Ford, Energy Manager**, **Trevor Kanerva, Chief Operating Engineer**, and the **Plant Operations Maintenance** and **Design Groups** for having done a superb job of fine tuning and maintaining the many services critical to cleanroom operations, and for leading the mechanical renovations (under **Carlos Radic**) for the new 100kV EBL system.

Special thanks to our two senior faculty members on the Quantum NanoFab Management Team, **David Cory, Scientific Director, IQC**, and **Tong Leung, Scientific Director, WIN**, for their continued excellent guidance in support of the Quantum NanoFab's vision of enabling world-class research via state-of-the-art facilities and professional operations.

Special thanks to **David Cory** for providing the funds needed to double the Oxford ALD system's precursor capacity to six.

Special thanks to **Steve Weiss & Team** for their excellent IT support which this year included the establishment of a software lab dedicated to Quantum NanoFab operations as well as the development of *TRAX*, a custom order entry and cost reporting software platform.

Final thanks go to all members of the **Quantum NanoFab Team**, including **Mary Lyn Payerl**, for their exceptional contributions. The facility's remarkable success over the past few years would not have been possible without their passion, dedication and hard work.

1. EXECUTIVE SUMMARY

This report summarizes the *Quantum NanoFab* core facility's key operational highlights for UW Fiscal Year 2015/16. This was a particularly significant period in that it represented the first full year of fab operations in the Lazaridis Quantum-Nano Centre.

The fab team grew with the addition of Melissa Floyd in the position of *Accounting & Admin Assistant*. Building infrastructure continues to be well maintained with unplanned events (power failures, etc.) having affected the cleanroom on some rare occasions. Effective responses from Plant Operations kept these from severely impacting operations. Several renovations were completed including those related to the new JEOL JBX-6300FS 100kV electron beam lithography (EBL) system, the acquisition and installation of which was funded by IQC.

Major operational highlights included the installation of multiple equipment interlocks to protect tools from unauthorized use. A software lab was established in QNC B211 in which design and analysis software packages are made available to all lab members. Matt Scott assumed oversight responsibilities for the Packaging Lab and Dylan Totzke of IQC's IT group did an excellent job of designing and rolling out a custom order entry and data logging S/W package dubbed *TRAX*. TRAX will allow better management of facility costs and will centralize & increase order placement efficiency.

Many new nanofabrication processes and equipment features were commissioned & released throughout the year. The 100kV EBL system was successfully installed and performed exceptionally well during on site qualification testing, handily beating out its factory acceptance test results. This reflects highly on the environmental stability of the Quantum-Nano Centre.

A total of 893 staff-led equipment training sessions were completed over the period September 2014 to April 2016. Of these 467 were completed in FY2015/16. Many outreach activities took place throughout the year including multiple tours & presentations as well as a basic nanofabrication training session held for *USEQIP* participants hosted by IQC.

Lab membership grew to 163 lab users under 36 Principal Investigators. Equipment use grew by 259% with respect to FY2014/15 with a total of 7752 hours billed, a new record. Trends at the time of publication suggest a further 40% to 50% growth in equipment use in FY2016/17.

Cost of operations grew by 36% to $1.049M. This is largely due to three factors: increase in salary costs by 26% (44% of total), increase in supplies and maintenance costs in part related to increased facility use (41% of total), and increase in nitrogen consumption costs (15% of total). Revenues from fees collected totaled $330k for the year, the full amount of which was applied against fab operating expenses.

Objectives for FY2016/17 include the hiring of an EBL scientist and the development of a training program geared towards independent end-user operation of the 100kV system. Co-op students, funded by IQC, will be hired to expand the facility's hours of operation. Their presence will allow the commissioning of several remaining pieces of equipment such as spin coaters etc. In terms of new equipment acquisitions, specifications will be defined for a new UHV angle evaporator system dedicated to high quality Josephson junction formation. Funded by IQC, the system will be accessible to all Quantum NanoFab lab members.

2. GOVERNANCE

In October 2010 the facility's management & operational plan received the approvals of Raymond Laflamme, Executive Director of IQC, and Arthur Carty, Executive Director of WIN. The plan remains in place in its original form: https://fab.qnc.uwaterloo.ca/governance

The Quantum NanoFab Management Team continues to meet once every four months to address high level issues and to discuss the facility's ongoing scientific and operational priorities.

3. PEOPLE

The Quantum NanoFab Team grew in FY2015/16 with the addition of Melissa Floyd. Melissa assumed the newly created role of *Quantum NanoFab Accounting and Administrative Assistant* in October 2015 and has been a welcome addition to the team. Previously on IQC's Admin Team, Melissa hit the ground running and immediately took over a wide range of activities including managing the new lab member application process, monthly invoicing and reconciliation tasks, order placement responsibilities for the entire team, etc.

Quantum NanoFab Team:

Equipment Technologists	Brian Goddard Rodello (Rod) Salandanan Matthew (Matt) Scott
Process Engineering	Nathan Nelson-Fitzpatrick
Cleanroom Certification & Inventory Specialist	Mai-Britt R. G. Mogensen
Accounting & Administrative Assistant	Melissa Floyd
Information Technology	Steve G. Weiss (1 day/week)
Accounting	Mary Lyn Payerl (1 day/week)
Director	Vito Logiudice

Management Team:

Faculty, Scientific Director, IQC	David Cory
Faculty, Scientific Director, WIN	Tong Leung
Director	Vito Logiudice

Leadership Team:

Executive Director (Interim), WIN	Holger Kleinke
Executive Director, IQC	Raymond Laflamme
Faculty, Scientific Director, IQC	David Cory
Faculty, Scientific Director, WIN	Tong Leung
Director	Vito Logiudice

Given the substantial growth in facility use over the past year a third, permanent *Equipment Technologist* position was created in December 2015 with the approvals of David Cory (acting Executive Director of IQC at the time), George Dixon (V.P. Research) and Ian Orchard (V.P Academic & Provost). In January 2016 the new position was posted internally consistent with UWaterloo hiring policies. Matt Scott began in this new permanent role on February 1, 2016.

With significant financial assistance from IQC, the Quantum NanoFab Management Team also worked out a plan for hiring one or two Co-op students on an ongoing basis starting May 2016. The presence of Co-op students will result in numerous benefits including:

- Moving several long-standing operational objectives forward including the development, characterization and documentation of multiple new nanofabrication recipes across a wide range of process equipment.
- Commissioning the last few pieces of equipment such as the Tystar polysilicon (PolySi) and low temperature oxide (LTO) LPCVD furnace tubes, the Brewer spin coater/bake systems and the Westbond semi-automatic wire bonder.
- Designing and carrying through multiple experiments as needed to develop and better characterize new and existing physical vapour deposition (PVD) recipes.
- Augmenting the breadth of available statistical process control data for the most commonly used deposition, etch and lithography recipes.

Further, the addition of Co-op students on the Quantum NanoFab Team will permit an expansion of the facility's existing full hours of operation, currently limited to 8AM to 6PM Monday to Friday. The facility's first hire will join the team in May 2016 and will eventually work from 2PM to 10PM Monday to Friday. This will allow the expansion of weekday fab hours to 10PM Monday through Friday for qualified, experienced lab members. The addition of a second Co-op student later in the year may also allow for week-end hours of operation. The facility's policy on its hours of operation will evolve to reflect these changes.

4. KEY ACTIVITIES & OPERATIONAL HIGHLIGHTS

This section presents a summary of the infrastructure and operational highlights over the period May 1, 2015 to April 30, 2016.

4.1. BUILDING & CLEANROOM INFRASTRUCTURE

The Quantum-Nano Centre's building systems continue to perform well with only a small number of unplanned events having affected fab operations over the course of the year. Facility downtime due to these events was limited to a very respectable 0.82% for a total of three "facility down" days over the course of the entire fiscal year.

- August 20, 2015: RO/DI water system failure. A technical issue caused a portion of the system's control programming to be lost. Fortunately UW's Plant Operations group under the leadership of Trevor Kanerva, *Chief Operating Engineer*, had already secured an ongoing service contract with *Evoqua Water Technologies* for maintaining and repairing the system. Evoqua was successful in returning the system to service within twelve hours of the original disruption.
- October 16, 2015: Main cleanroom exhaust system failure. The control board for the main and redundant exhaust fans that serve the cleanroom was damaged during a major overnight rainstorm. Plant Operations and the 3rd party contractor hired to maintain these and all other QNC building control systems, *Johnson Controls*, performed admirably and succeeded in keeping facility downtime to less than ten hours after the initial event. Of note, a member of the local Johnson Controls crew, Brian Cimbron, drove to Mississauga to retrieve a replacement control board soon after the failure. These actions were instrumental in limiting facility downtime.
- October 26, 2015: One of the building's two main water feeds burst. This affected the building's process chilled water (PCW) loop and also caused flooding and damage to one of the building's Concourse level mechanical rooms. The incident caused a partial Quantum NanoFab shutdown of approximately twenty-four hours. The impact of the situation could have been significantly worse had it not been for the near-immediate response of UW's Plant Operations group. Their actions played a significant role in minimizing equipment damage and shut down duration, and their well thought out temporary fix kept the building from having to be completely closed down.
- January 27, 2016: A false reading on a Methylsilane gas sensor triggered the cleanroom's Toxic Gas Monitoring System (TGMS). The situation was immediately assessed and stabilized thus causing only a few minutes' impact to

cleanroom operations. It had been known for some time that the cartridge in this particular sensor was also sensitive to solutions of IPA which are routinely used for cleaning the cleanroom walls and floors. On this particular day several floor tiles in the service bay near the gas sensor in question had been removed to effect work related to the 100kV EBL system installation. It's believed that the open floor sections caused IPA vapour concentrations to exceed the sensor's "alarm level 2" set point which thus caused it to trigger the TGMS system's evacuation function. The problem was permanently resolved by replacing the original gas sensor cartridge with another type of unit which is less sensitive to IPA but which remains appropriately sensitive to Methylsilane gas.

- January 29, 2016: Campus-wide power failure. The building's emergency generator performed quickly & flawlessly and the cleanroom's automated ventilation & exhaust control sequences performed as expected. The cleanroom's supply and exhaust fans are on emergency power. This maintained lab pressurization relative to the rest of the building throughout the event thus limiting facility downtime to just a few hours after power was restored.
- April 2016: RO/DI water system failure. Communication issues caused the system to shut down unexpectedly. Plant Operations quickly resolved the problem and no serious impacts to cleanroom activities were noted.

The Plant Operations Maintenance Group also did a good job of staying on top of routine building maintenance and repair. These planned activities resulted in minimal facility downtime of approximately 2.0%. Of note, planned downtime included the following one-time upgrade, renovation and system installation activities:

- August 2015: Annual campus-wide steam system shutdown for routine maintenance was completed as planned. The shutdown affected humidity control in the cleanroom over the course of two days. This impacted lab members wishing to perform advanced lithography work but all other process capabilities remained available.
- October 2015: Annual DI water system maintenance and distribution loop sanitization completed as planned. This affected processes requiring the use of DI water for a period of approximately 24 hours.
- December 2015: The cleanroom was shut down for a total of three days to complete an upgrade of the building's bulk nitrogen gas supply system which included the addition of a 2nd evaporator on the exterior N_2 pad. In parallel, the Fab Team took the opportunity to complete major construction activities related to the installation of the 100kV E-beam lithography system. System delivery was planned for February 2016.

- February 2016: The cleanroom was shut down on February 2nd to allow for the physical installation of the 100kV EBL system in cleanroom module 1701M.
- April 2016: The cleanroom was shut down for four hours on April 8th to allow for exhaust fan system maintenance.
- Over the course of the year the Plant Operations Maintenance Group changed the primary, secondary and tertiary filters on the two makeup air units that serve the cleanroom. The design of the air supply system is such that filter changes can be completed on either makeup unit independent of the other. Ie., air pressurization in the cleanroom relative to the rest of the building is automatically maintained by the PLC-based control system during such activities, even if one of the two units is shut down for maintenance. Air filter changes have thus had no impact on operations. This is consistent with original design objectives.

Temperature and humidity control throughout the facility remain generally excellent. The extremely stable 48 hour temperature trend in e-beam lithography bay 1701M shown in figure 1 is a testament to the excellent work done by Plant Operations in tuning building controls to the extent needed to ensure successful installation and commissioning of the JEOL EBL system (see section 4.3 & Appendix B).

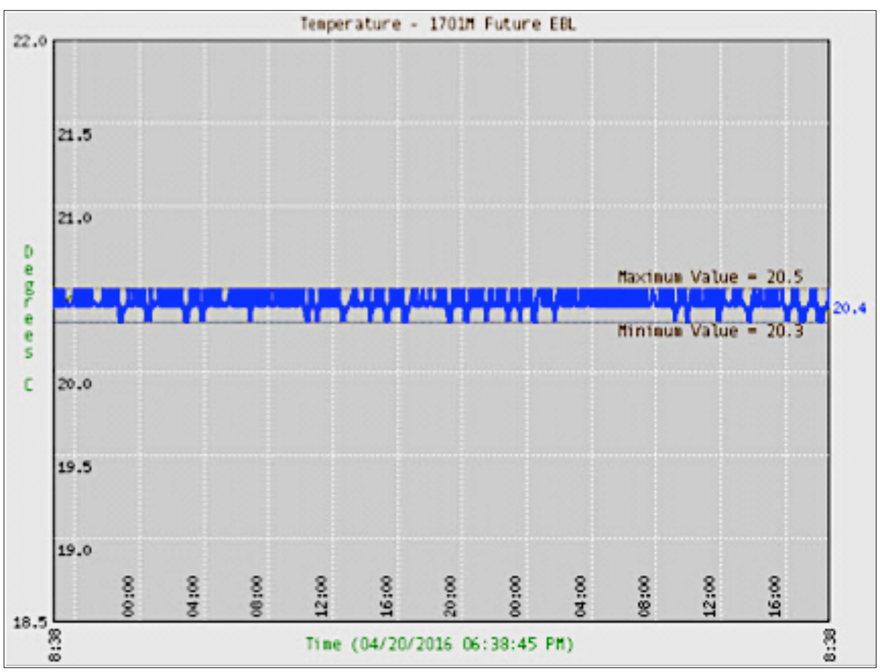


Figure 1: 48 hour temperature trend in 100kV e-beam lithography module
Stability is well within the specification of no more than ±0.1 °C drift

4.2. CLEANROOM GENERAL OPERATIONS

Several important milestones were reached and new records hit over the course of the year:

- Fifty one individual pieces of lab equipment may be independently booked for use in the Quantum NanoFab's *Badger Lab Management System* (LMS) software platform. Of these, 36 tools were physically interlocked with Badger over the course of the year; see Appendix A for a listing of interlocked equipment. All 36 systems now remain disabled/unusable unless a user wishing to gain access to any one of these has the necessary credentials (ie., training & authorization) assigned to them in Badger. This diminishes the risk of equipment damage or contamination due to misuse.
- Responsibility for the entire toolset located in Packaging Lab 1706 was placed under Matt Scott's leadership. Matt was named lead trainer for this lab in mid-2015 and has since published several standard operating procedures (SOP's) for the equipment housed in this lab.
- The "*QNC Cleanroom & Satellite Labs Power Down Check List (Long Term)*" standard operating procedure was updated to include the safe shutdown procedure for the 4-tube furnace as well as all Packaging Lab equipment.
- Under the leadership of IQC's IT group (Cory Brown & Steve Weiss), a new software lab was established in room QNC B211. This lab is host to several computers and thus provides access to multiple design and analysis packages to the entire Quantum NanoFab lab member community. Available S/W packages include:
  - Juspertor – Layout editor (CAD S/W for photomasks & EBL patterns)
  - Raith GDSII Editor (CAD S/W for Raith 150TWO EBL)
  - GenISYS - BEAMER & TRACER (advanced CAD for JEOL EBL)
  - Woollam completeEASE (ellipsometry data analysis)
- Under Melissa's leadership and with the help of IQC's IT group, the facility's invoicing mechanism was repatriated from *Badger LLC* in late 2015. Mike Bell of Badger had graciously assumed responsibility for generating all monthly invoices until the accounting & administration position on the team was filled. Since late 2015 invoices have been generated in-house and are typically sent to Principal Investigators within three to four weeks of any given month-end. Mary Lyn Payerl plays an important role in these invoicing activities; her contributions are gratefully acknowledged.
- Dylan Totzke with IQC's IT group worked closely with Melissa Floyd to develop a custom, password-protected order placement and cost tracking software package dubbed *TRAX*. TRAX allows all Quantum NanoFab team members to place material orders via this central platform. TRAX also allows for immediate categorization and storing of Quantum NanoFab expenses. These functions coupled with the platform's reporting capabilities will permit the establishment of a facility cost model which will serve to identify the cost of

running each major piece of lab equipment on a tool-by-tool basis. This data coupled with historical equipment use records may be used in the future to adjust access rates to better reflect the actual cost of maintaining and operating each piece of equipment. TRAX data coupled with Badger equipment use data will also help identify underused pieces of equipment which may be inordinately costly to maintain. This will provide management with the information needed to assess whether the community might be better served by the removal and replacement of these particular tools with new, more useful equipment. TRAX will be rolled out and adopted by the entire fab team on May 1, 2016.

Dylan Totzke's significant contributions towards this project are gratefully acknowledged.

- Packaging Lab access hours were expanded to include 24/7 access for qualified, advanced lab members.
- A total of 7752 hours of equipment use was billed over the course of this fiscal year, a new record. A breakdown of the number of hours billed per tool is shown in figure 2.

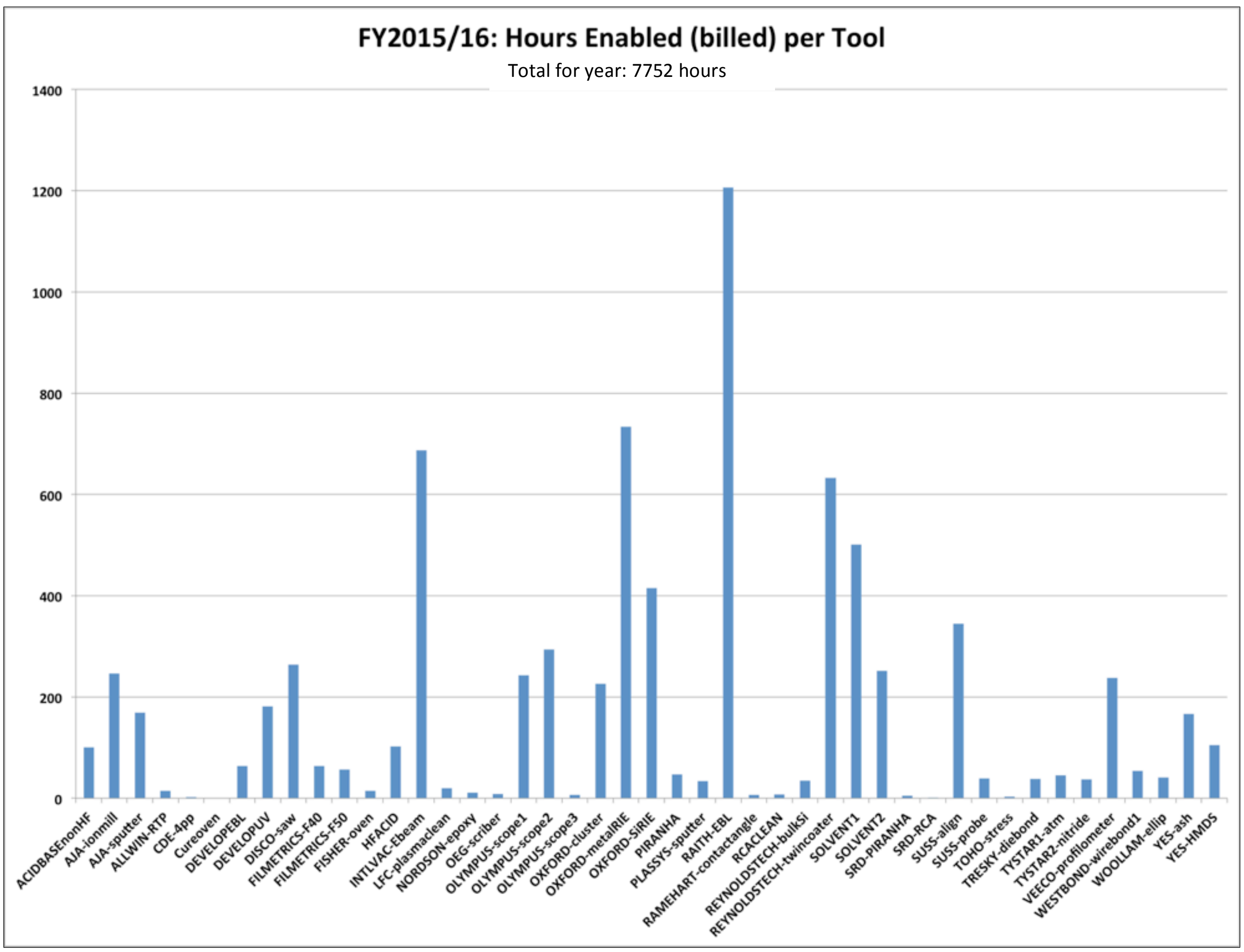


Figure 2: Hours enabled per tool over the course of the year

- Figure 2 confirms that the most commonly used tools include the Raith 150TWO 30kV e-beam lithography exposure system, the Oxford III-V & metals etcher, the Intlvac e-beam evaporator, the spin coat and solvent hoods as well as the Oxford fluorine etcher dedicated to silicon etch.

4.3. LAB EQUIPMENT & NEW PROCESSES

The fab team was also kept busy with multiple new process development and characterization initiatives as well as with a major equipment installation project.

- May 2015: SIMS endpoint detection function on AJA Ion Mill characterized, documented & released for general use.
- June 2015: Woollam ellipsometer commissioned & released for general use.
- July 2015: Bag purge/vacuum sealer installed in the cleanroom. The sealer allows members to package their samples in an inert atmosphere in moisture resistant & ESD-rated bags, thus protecting them from damage when transported to other labs for further processing or analysis.
- HSQ photoresist for e-beam lithography introduced in August 2015. HSQ is a negative resist that complements the existing PMMA & ZEP positive resists already available in the fab. HSQ offers exceptional resistance to etch processes and is known for its high contrast & resolution performance.
- August 2015:
    - Thanks to excellent tool oversight and careful planning by Rod Salandanan, the Cryo pump on the INTLVAC e-beam evaporator was replaced in record time. After five years of faithful service, a replacement for the aging pump was ordered well in advance of the unit's anticipated failure and tool downtime was therefore limited to less than 24 hours.
    - *West Bond* manual wire bonder commissioned & released for use.
    - High purity CH_4 & H_2 process gases commissioned for use on the Oxford metal etch ICP RIE system.
    - Tystar furnace tube 1 (thermal oxidation) characterized and released for use.
    - Tystar furnace tube 2 (silicon nitride deposition) characterized and released for use.
- September 2015:
    - AJA sputter system characterized and released for use.
    - New processes for dicing sapphire and alumina substrates on the DISCO DAD 3240 dicing saw were released for general use.
    - JEOL EBL system site plan and scope of renovations were finalized.
    - UPS for new EBL ordered.
- October 2015: Work Request for JEOL EBL renovations submitted to UW Design group.
- November 2015: Site renovations for JEOL EBL began.

- December 2015: Bulk Si Etch fume hood commissioned & released for use.
- January 2016:
    - New InAs & InP etch recipe making use of H_2 & CH_4 process gases developed & documented by lab member Denis Striakhilev with the help of Craig Ward (*Oxford Instruments*) and Nathan Nelson-Fitzpatrick. Recipe details are available online to entire fab membership (document name *PROC_InAs_InP_DRIE.pdf*).
    - RCA Cleans fume hood commissioned and released for use.
    - ALD precursor cabinet upgrade completed: a total of six liquid precursor positions are now available on the system up from three. Upgrade was made possible via generous funding from David Cory. TEMAH precursor has since been added to allow for the deposition of Hf & HfO_2 thin films.
    - E-gun on INTLVAC e-beam evaporator failed. E-gun was replaced with a spare unit acquired in 2013, thus limiting system downtime. The failed gun has since been repaired & is kept on site as a backup unit.
- February 2016: New JEOL EBL system delivered and physically located in cleanroom module 1701M. IQC generously provided the $3M in funds for system acquisition and installation.
- March 2016: Service contract for all three Oxford tools was renewed for 3 additional years.
- April 2016: JEOL EBL successfully commissioned in record time. Startup activities took 8 weeks to complete rather than the 14 weeks originally planned by JEOL. This is in large part thanks to the exceptional efforts of the JEOL Team: Ryo Funakoshi-san, Brian Legge, Tong Liu, Mike Maguire and Ron Snios, as well as Quantum NanoFab team members Brian Goddard, Matt Scott and Nathan Nelson-Fitzpatrick. On site commissioning test results are shown in Appendix B. Some of these exceeded the performance of the factory test results completed in Japan. This is further confirmation of the Quantum-Nano Centre's exceptional environmental stability.

Figure 3: 6300 lb JEOL main console being moved into cleanroom

Figure 4: Fully commissioned JEOL JBX-6300FS in its new home in the Quantum NanoFab

4.4. TRAINING, TECHNICAL SUPPORT & OUTREACH

Continued growth in fab membership kept the fab team busy with a total of 893 equipment training sessions completed since Sept. 2014. Figure 5 shows a breakdown of the sessions completed per tool over the period Sept. 2014 to April 2016.

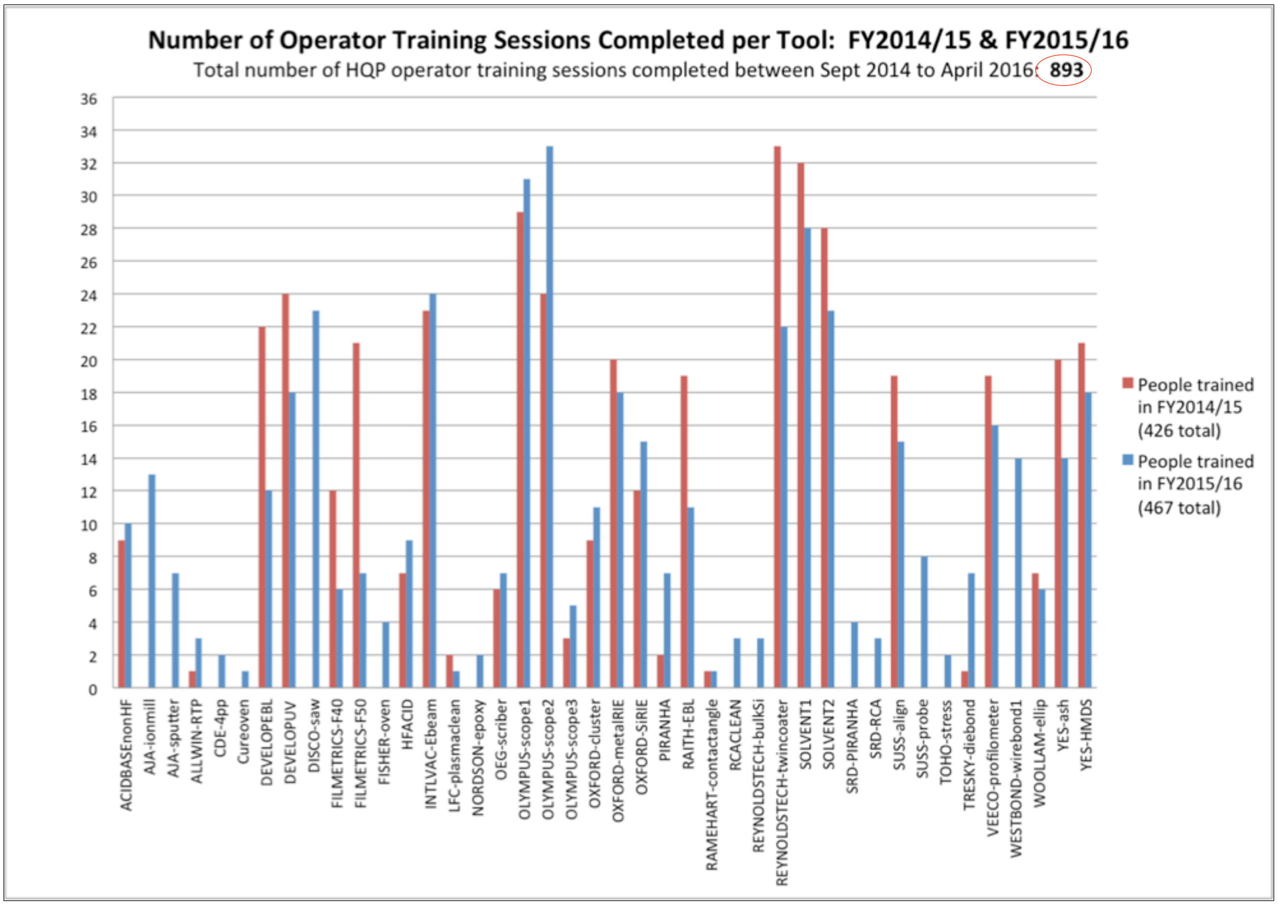


Figure 5: Equipment operator training sessions completed per tool over past 2 years

Detailed and revision-tracked standard operator procedures (SOP's) form the foundation of all hands-on equipment training sessions. These have served to standardize training modules for each piece of individual equipment, thus ensuring that all new users are trained rigorously & consistently. This helps everyone make best and safe use of all lab equipment. Hands-on sessions are followed by tests during which the user must demonstrate the ability to independently operate a tool before being granted Badger credentials for enabling and using it. Similarly, much work is planned for the second half of 2016 to develop an in-depth training program for the complex JEOL 100kV e-beam litho system. Equipment users will benefit from a rigorous theoretical and practical training program which will help them make most effective use of the system. Many sites equipped with these types of tools do not typically allow end users to operate them directly. It is anticipated that the opportunity to operate the system will allow members to develop a more in depth understanding of the tool's capabilities thus enhancing their experience and benefiting their overall research efforts.

In FY2015/16 fab staff provided a total of 470 hours of support to lab members. The per-month breakdown of both technical and equipment training support is detailed in figure 6:

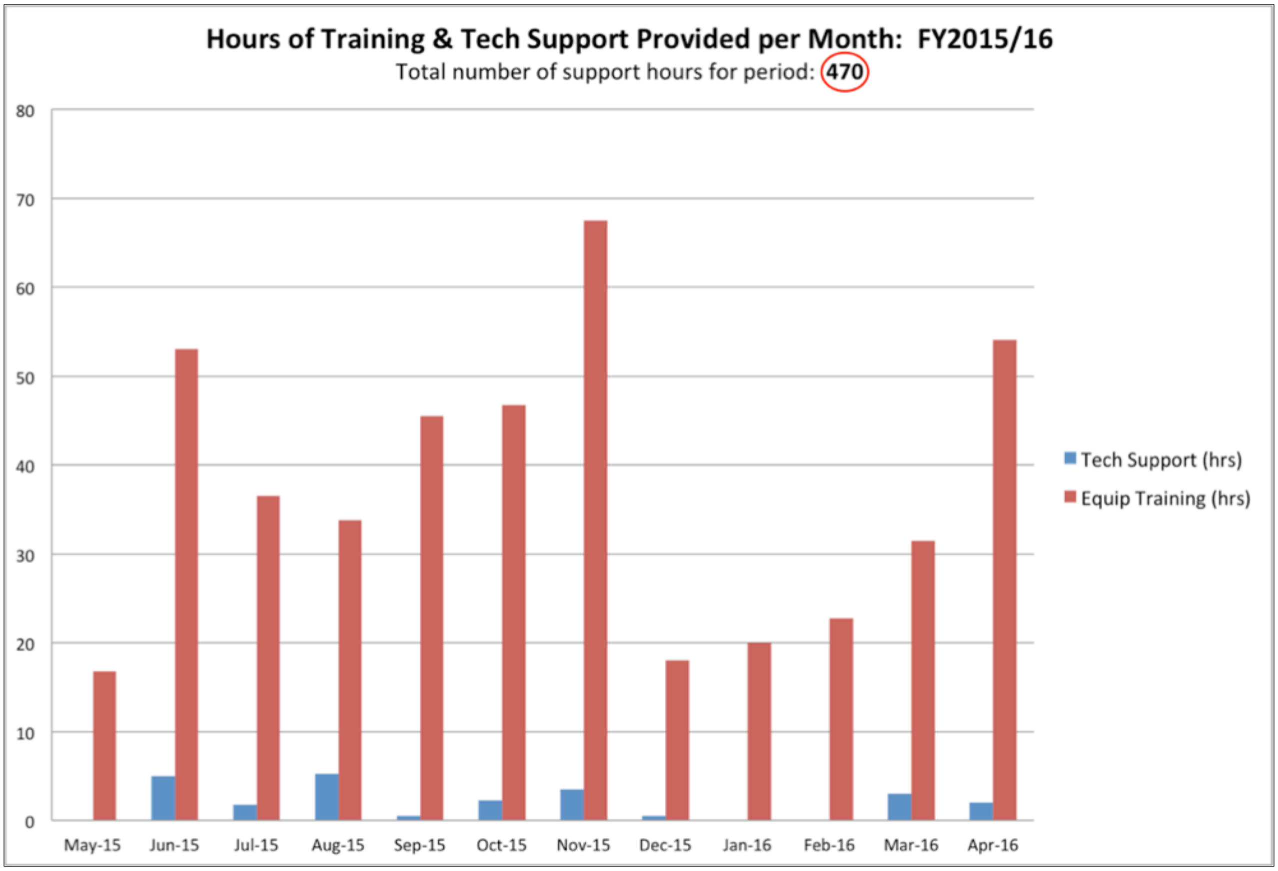


Figure 6: Per month hours of equipment training & tech support provided

Multiple outreach activities took place over the course of the year. These benefit the broader community both within and outside the university by:

- Informing the public of the existence of and importance of these types of facilities for a broad range of research activities spanning the sciences and engineering.
- Making potential new faculty hires and students aware of the infrastructure and its excellent capabilities and professional operations.
- Providing basic cleanroom and nanofabrication training to young researchers from around the globe.

- Making potential customers aware of the existence of the state-of-the-art infrastructure available at UWaterloo.

Some noteworthy outreach activities in FY2015/16 include:

- May 2015: Tradeline *Conference on Core Facilities*, St. Petersburg FL; Talk titled "Lessons Learned in Nanofabrication Cleanroom Construction and Start-up" co-presented by Jack Paul (*HDR Architecture*) & Vito Logiudice. Conference participants voted the presentation "*the #3 top-rated forum session of the conference*".
- May 2015: Nano-Ontario workshop on "*Nanofacilities for Emerging Technologies, Industry-University Showcase*" hosted by UWaterloo; Quantum NanoFab overview presented by Vito Logiudice.
- July 2015: USEQIP 2015 organized by IQC: University students from around the world spent two days in the cleanroom in July 2015 learning about basic nanofabrication techniques under the guidance of two experienced Quantum NanoFab lab members, Carolyn Earnest & Corey Rae McRae, both IQC PhD students.
- October 2015: *Quantum Innovators Workshop* organized by IQC; Quantum NanoFab overview presented by Vito Logiudice.
- Multiple tours given to faculty candidates, including window & full interior tours.
- Countless window tours including UWaterloo's Board of Governors.
- Interior tour given to *Voltera*, local UWaterloo *Velocity* funded startup.

Figure 7: Voltera startup founders & employees stand next to new JEOL system

Figure 8: USEQIP participants being supervised by IQC PhD student Corey Rae McRae as they use the Suss-Microtec MA6 mask aligner

4.5. SAFETY

There are no injuries or incidents to report for FY2015/16. The facility's comprehensive safety, cleanroom behaviour and equipment operator training programs continue to serve the community well.

As required by provincial legislation, safety inspections of the cleanroom and all satellite labs continue to be completed on a monthly basis. Paper copies of these inspections are kept in the cleanroom gowning room bay and may be freely viewed by all registered lab members and UW personnel. Electronic copies are also kept online and may be viewed remotely as required.

A series of activities were undertaken this past year to further enhance lab safety:

- *Ontario Ministry of Labour* came to site on January 26 & 27, 2016 and completed a thorough safety inspection of the Lazaridis Quantum-Nano Centre. No issues were identified in the Quantum NanoFab cleanroom or in any of its satellite labs.

- Newly legislated WHMIS 2015 training requirements were completed by all staff members and a large majority of Quantum NanoFab lab members by March 1, 2015. People whom did not complete the training by the deadline saw their facility access privileges suspended until program completion.

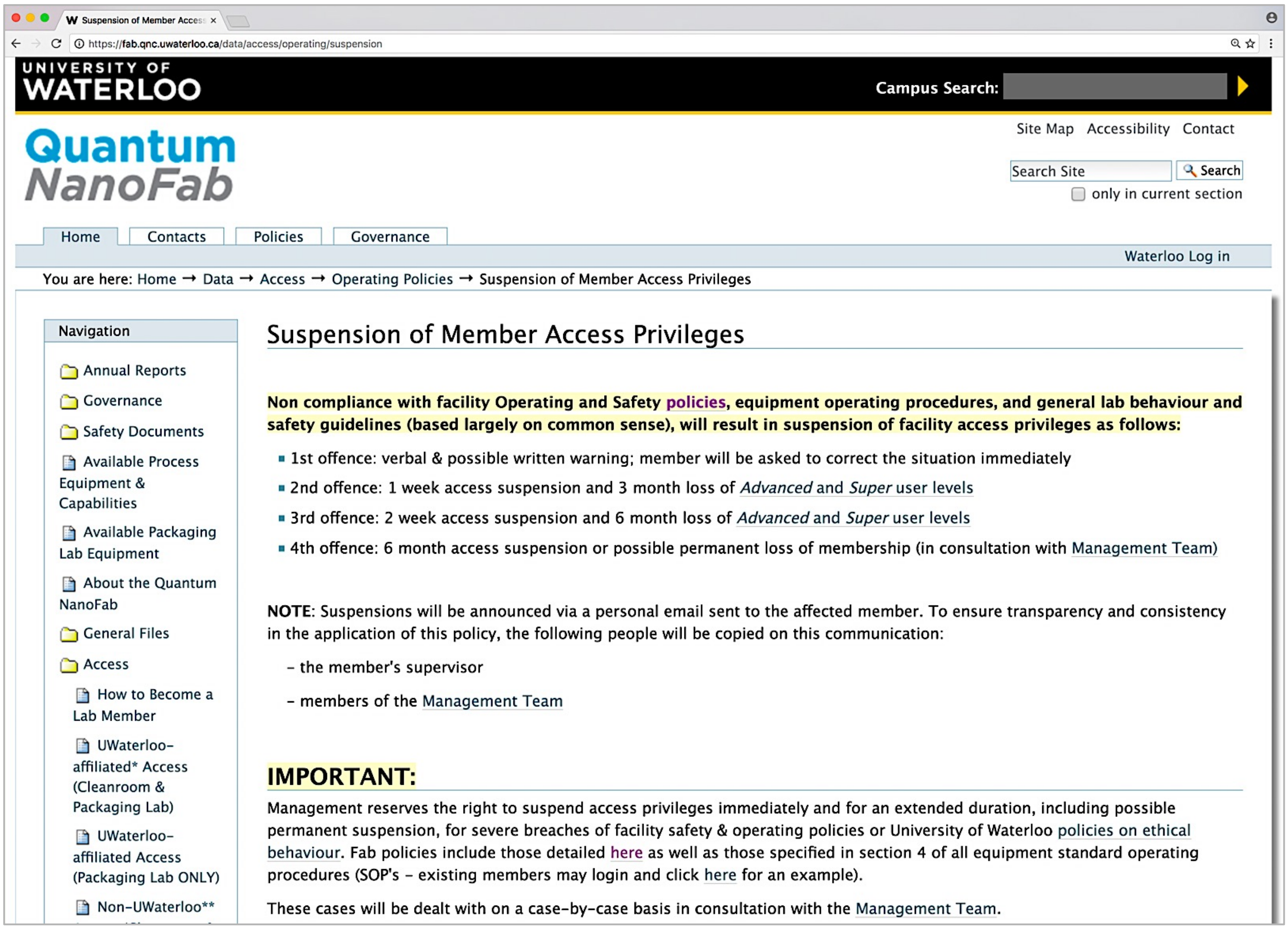
- March 2, 2015: New policy created to enhance safety for lab members whom have been away for an extended period of time. Starting March 2, 2015 people whom have been absent for six months or more will have their access privileges suspended. Affected lab members wishing to regain access may do so by completing three online video training programs covering the subjects of behaviour in cleanrooms, contamination control and safety.

- March 2016: Several malfunctioning gas cabinet exhaust sensors were replaced or repaired. Programming issues with the Honeywell TGMS system were also identified and addressed. Several TGMS gas cartridges were replaced in advance of their expiration dates.

- April 2016: Matt Scott joined the University of Waterloo's *Hazardous Spills Team*. The Spills Team now includes two Quantum NanoFab staff members: Matt Scott & Vito Logiudice.

4.6. LAB MEMBER SUSPENSIONS

The facility's policy on suspension of member access privileges is posted on the Quantum NanoFab's public online portal: https://fab.qnc.uwaterloo.ca/data/access/operating/suspension



W Suspension of Member Access ×

https://fab.qnc.uwaterloo.ca/data/access/operating/suspension

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Suspension of Member Access Privileges

Non compliance with facility Operating and Safety policies, equipment operating procedures, and general lab behaviour and safety guidelines (based largely on common sense), will result in suspension of facility access privileges as follows:

- 1st offence: verbal & possible written warning; member will be asked to correct the situation immediately
- 2nd offence: 1 week access suspension and 3 month loss of *Advanced* and *Super* user levels
- 3rd offence: 2 week access suspension and 6 month loss of *Advanced* and *Super* user levels
- 4th offence: 6 month access suspension or possible permanent loss of membership (in consultation with Management Team)

NOTE: Suspensions will be announced via a personal email sent to the affected member. To ensure transparency and consistency in the application of this policy, the following people will be copied on this communication:

- the member's supervisor
- members of the Management Team

IMPORTANT:

Management reserves the right to suspend access privileges immediately and for an extended duration, including possible permanent suspension, for severe breaches of facility safety & operating policies or University of Waterloo policies on ethical behaviour. Fab policies include those detailed here as well as those specified in section 4 of all equipment standard operating procedures (SOP's - existing members may login and click here for an example).

These cases will be dealt with on a case-by-case basis in consultation with the Management Team.

A total of twelve written warnings were issued to ten different lab members over the course of the year. Four members each received 2-week access suspensions for various policy violations. One member received a 4-week access suspension.

5. LAB MEMBERSHIP

Table 1 lists the names of the 36 Principal Investigators registered as Quantum NanoFab lab members as of April 30 '16. Ninety projects have been registered to date.

Table 1: Registered Principal Investigators as of April 30, 2016

Name	IQC	WIN	Other
Abdel-Rahman, Eihab		X	
Aitchison, Stewart			University of Toronto
Aziz, Hany		X	
Bajcsy, Michal	X		
Ban, Dayan		X	
Baugh, Jonathan	X		
Budakian, Raffi	X		
Cory, David	X		
Cui, Bo		X	
Hodgson, Chad			Transonic Scisense
Karim, Karim		X	
Knights, Andy			Ranovus
Laflamme, Raymond	X		
Lupascu, Adrian	X		
Maheshwari, Vivek			VELOCITY
Majedi, Hamed		X	
Makarov, Vadim	X		
Mansour, Raafat		X	
Mariantoni, Matteo	X		
Mayer, Michael			UW Mech Eng
Miao, Guo-Xing	X		
Nazar, Linda		X	
Pawliszyn, Janusz		X	
Perumal, Veeramani			Redlen Technologies
Reimer, Michael	X		
Ren, Carolyn		X	
Safavi-Naeini, Safieddin			UW Elec Eng
Sciaini, German		X	
Saini, Simarjeet		X	
Teklemariam, Grum			High Q Technologies
Tsen, Wei	X		
Wang, Xiaosong		X	
Wasilewski, Zbig		X	
Wilson, Christopher	X		
Yavuz, Mustafa		X	
Yeow, John		X	
TOTAL	**12**	**16**	**8**

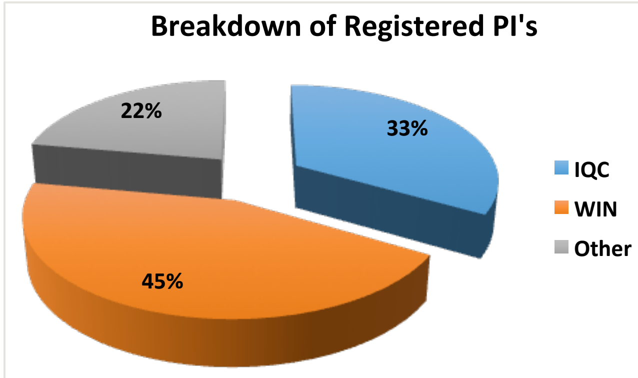
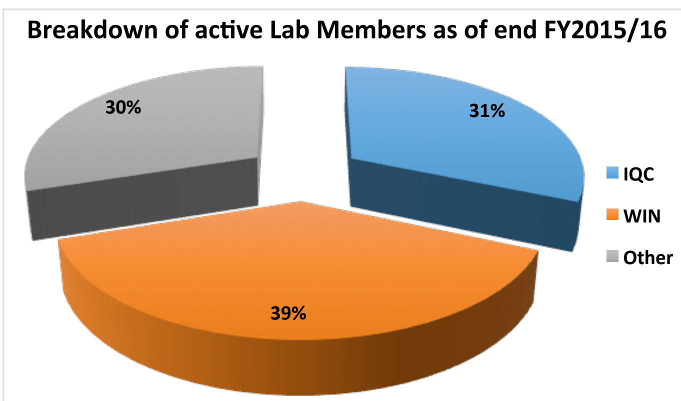


Table 2 shows the total number (70) and breakdown of active lab members over the course of FY2015/16 whom worked under the 36 PI’s listed in table 1.

Table 2: Breakdown of active Lab Members (users) as of end FY2015/16

Category	IQC	WIN	Other	TOTAL
Co-op Students	1	2	1	4
Undergraduate Students	3	0	0	3
Graduate Students	12	14	12	38
Post-Doctoral Fellows	6	10	1	17
Other	0	1	7	8
TOTAL:	**22**	**27**	**21**	**70**



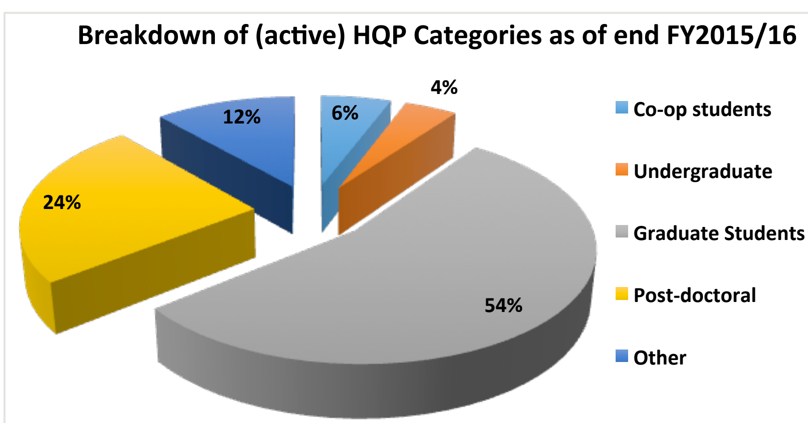
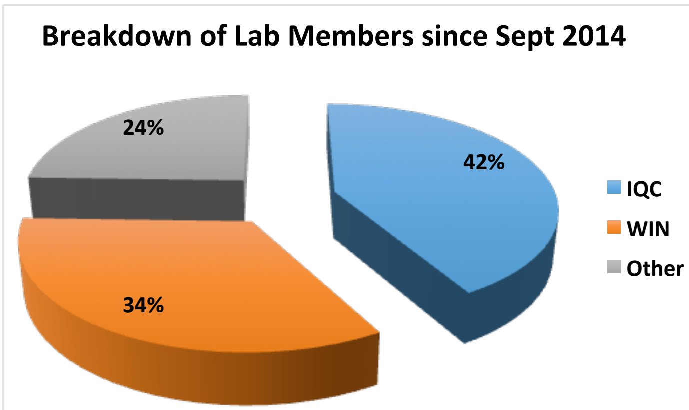
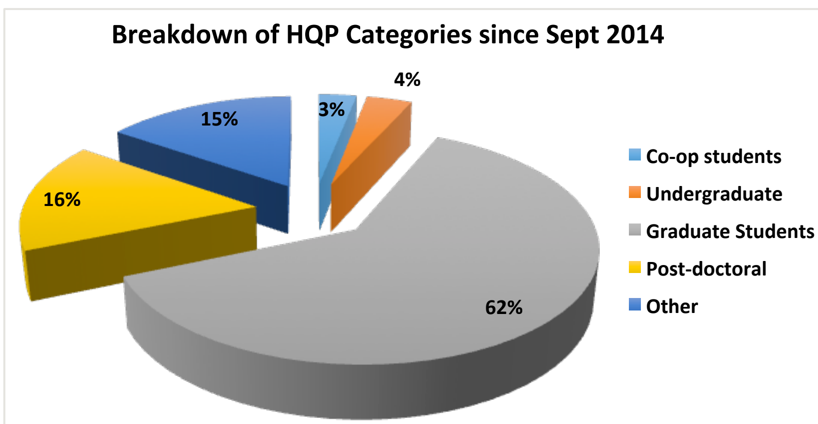


Table 3 shows the total number (163) and breakdown of lab members trained since operations first began in the Lazaridis Centre in September 2014.

Table 3: Breakdown of Lab Members (users) since Sept. 2014

Category	IQC	WIN	Other	TOTAL
Co-op Students	1	2	2	5
Undergraduate Students	5	0	1	6
Graduate Students	41	38	22	101
Post-Doctoral Fellows	10	13	3	26
Other	11	2	12	25
TOTAL:	**68**	**55**	**40**	**163**





5.1. SAMPLING OF DEVICES FABRICATED BY MEMBERSHIP IN FY2015/16

Appendix C lists the 90 project titles registered with the Quantum NanoFab since September 2014.

An ensemble of devices built in the Fab by select members of its community is presented in the following pages. This is but a small sampling of the research activities that have been enabled by the facility over the past few years. All six submissions are from IQC members; their contributions are gratefully acknowledged.

Regrettably, no submissions were received from WIN or non-affiliated members.

RUBAYET AL MARUF, PHD STUDENT, BAJCSY GROUP (IQC)

The following images show a superconducting nanowire used as a single-photon detector. The device was fabricated by Rubayet Al Maruf in Prof. Bajcsy's group.

"We are trying to design and fabricate a Superconducting nanowire single photon detector (SNSPD) evanescently coupled to silica waveguides, such as fibers or laser written waveguides. This device is expected to have high overall system efficiency compared to SNSPDs evanescently coupled to Si waveguides. For the detector, we are using NbN nanowire with width ~100 nm and thickness ~6 nm. The feature is formed by reactive ion etching of an evaporated NbN film with HSQ-PMMA mask defined through Raith150 Two e-beam lithography."

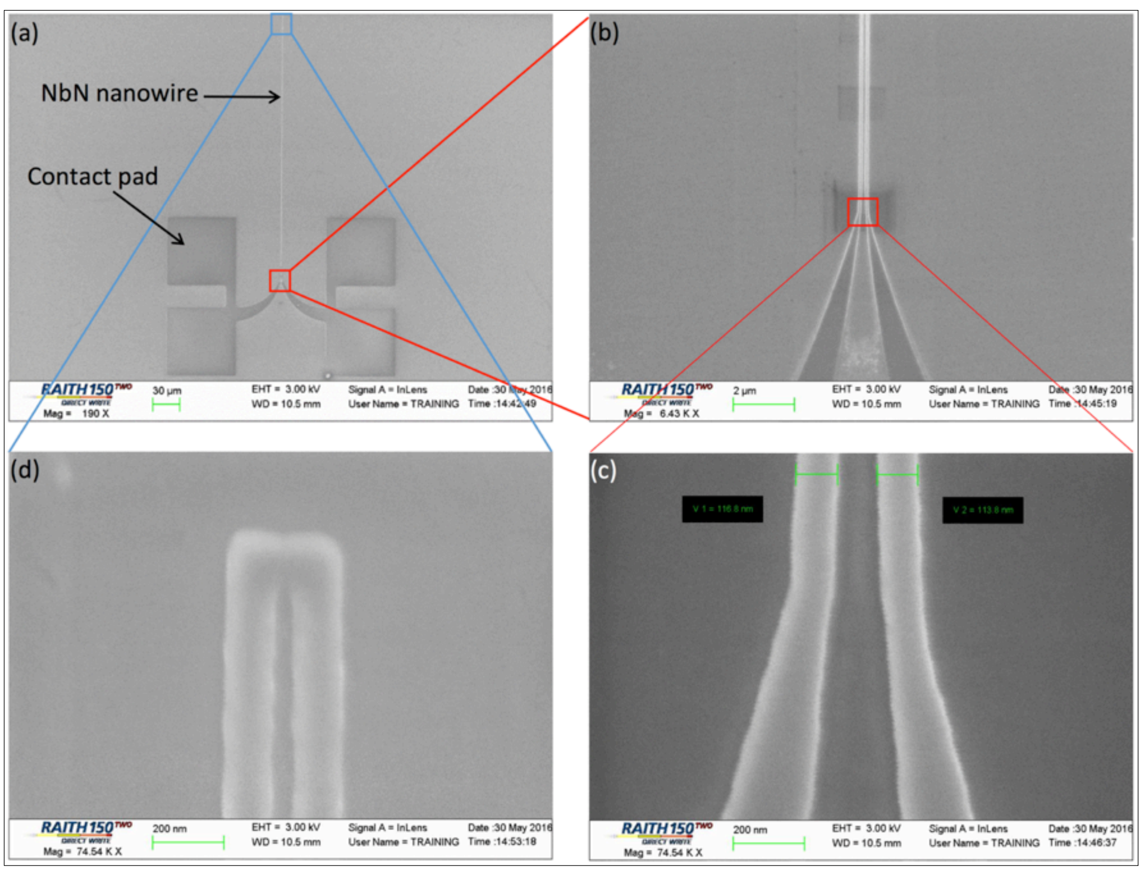


Figure 9:

(a) Superconducting nanowire for a single-photon detector (to be evanescently coupled to a laser written waveguide) made using NbN.

(b) Neck of the nanowire

(c) ~115 nm wide nanowire with ~100 nm gap in between them.

(d) Top of the nanowire.

(R. Al Maruf)

The following images show an on-chip splicer for coupling optical fibers, also fabricated by Rubayet Al Maruf in Prof. Bajcsy's group.

" Interfacing Hollow core photonic crystal fibers (HCPCF) with conventional single mode fibers (SMF) presents a unique set of challenges because of the empty (air filled) core in the HCPCF and the diameter mismatch between HCPCF and SMF. Here we have designed and fabricated an on-chip fiber splicer with which we can splice HCPCF and SMF with very low loss (<5%). The structure is formed in SU8-50 photoresist with UV lithography, while the alignment between fiber cores is achieved by etching a step in the silicon substrate."

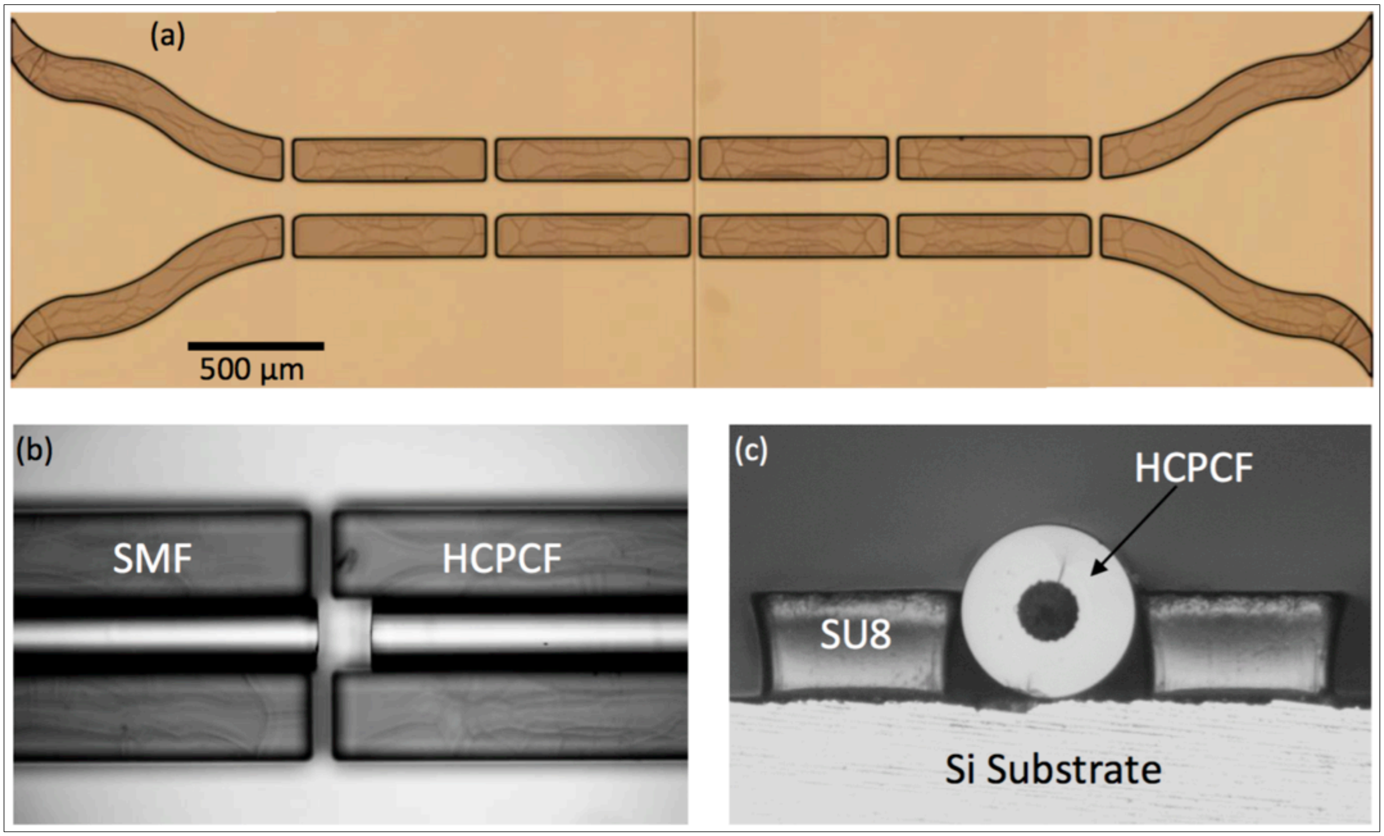


Figure 10: (a) On-chip splicer for coupling Hollow core photonic crystal fiber and solid core single mode fiber. (b) Splicer with SMF and HCPCF inserted from opposite sides. (c) Cross section of the splicer with HCPCF mounted.

(R. Al Maruf)

JEREMY FLANNERY, PHD STUDENT, BAJCSY GROUP (IQC)

The following images show a photonic crystal membrane designed to be highly reflective at a specific wavelength. This work was undertaken by Jeremy Flannery in Prof. Bajcsy's group.

"An optical image of a photonic crystal membrane with an inset showing a scanning tunnelling electron (SEM) image of the photonic crystal region. This device is designed to act as a highly reflective mirror for particular wavelengths of light. The optical and SEM scale bars correspond to 20 micrometers and 2 micrometers, respectively."

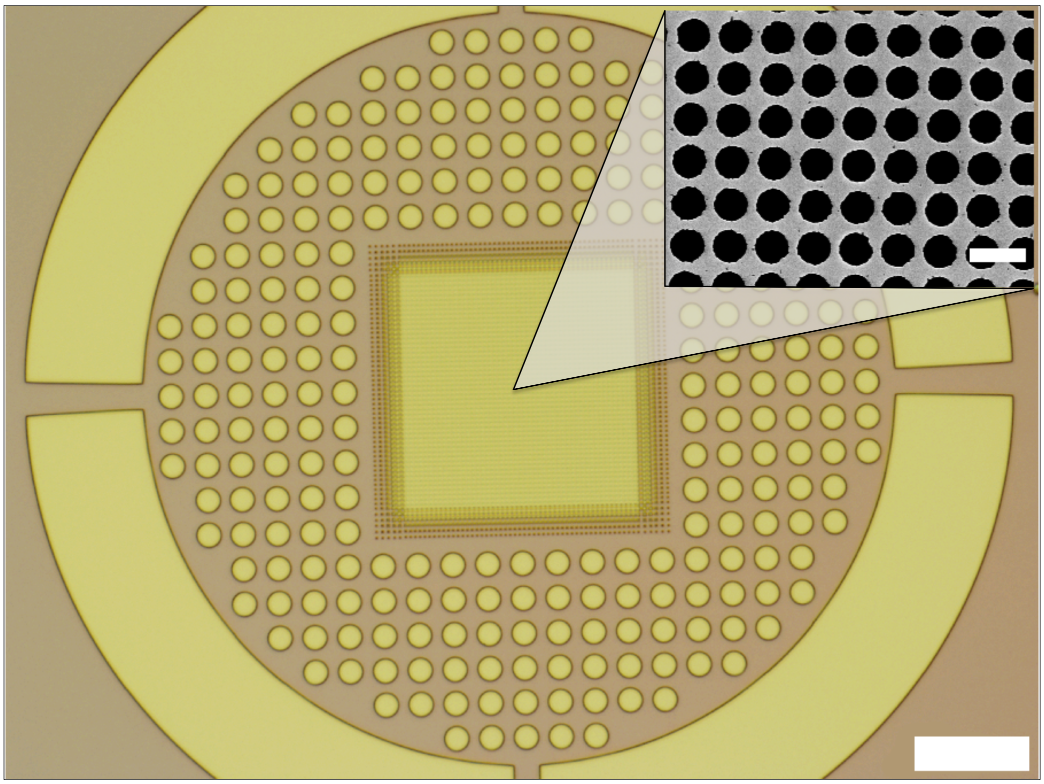


Figure 11: Photonic crystal membrane (J. Flannery)

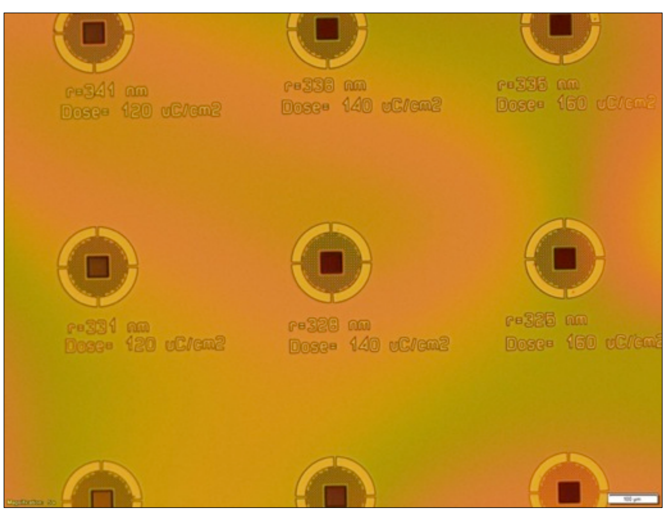


Figure 12: Photonic crystal membrane array, post develop (J. Flannery)

POL FORN-DIAZ, POSTDOCTORAL FELLOW, WILSON GROUP (IQC)

The following images show a superconducting flux qubit and surrounding drive circuitry. The device was fabricated by Pol Forn-Diaz in Prof. Wilson's group.

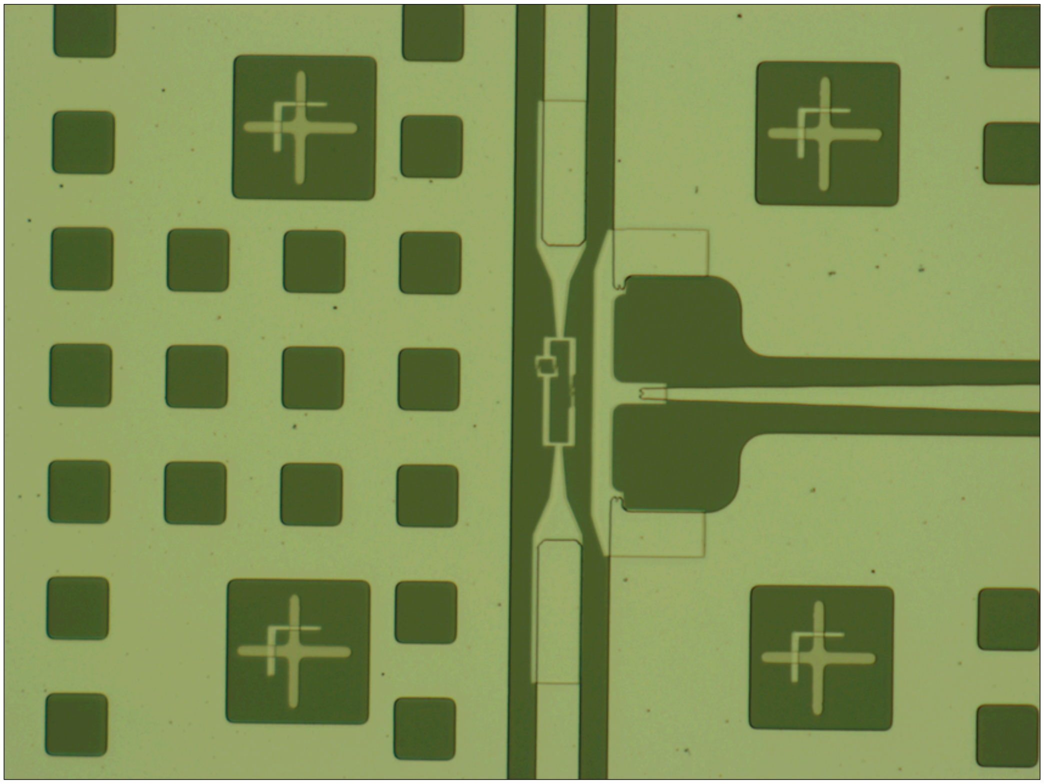


Figure 13: Optical image of superconducting flux qubit (center of the image) connected to a transmission line. Right of the qubit sits a microwave antenna to drive high-frequency signals to control the qubit state. Scale of picture is 0.2mm (horizontal width).

(P. Forn-Diaz)

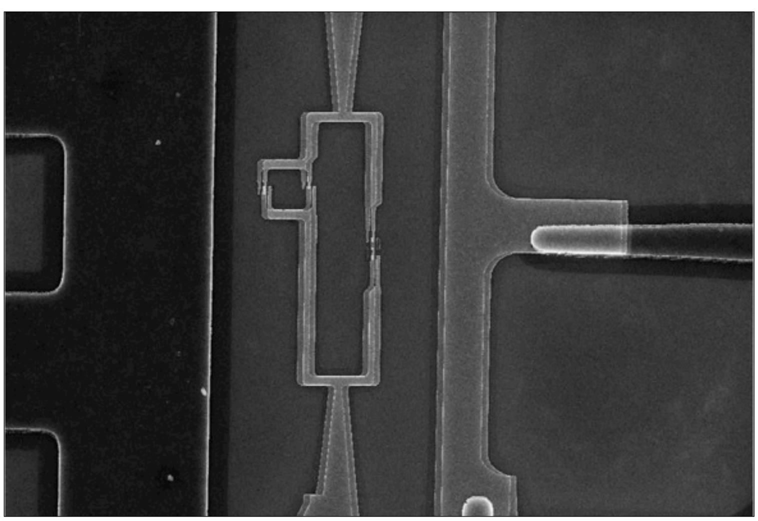


Figure 14:
Scanning electron microscope image of superconducting flux qubit formed by two loops. Within each loop several Josephson junctions are visible as small brighter areas where the metal-metal connection is interrupted. Scale of picture is 25um (horizontal width).
(P. Forn-Diaz)

SANDRA GIBSON, POSTDOCTORAL FELLOW, REIMER GROUP (IQC)

The following images show single nanowire field effect devices fabricated by Sandra Gibson in Prof. Reimer's group.

"These devices are InP nanowires deposited on a pre-fabricated array of Ti/Au back gates with hafnium oxide dielectric layer. I used the Raith to contact the nanowires and gates for measuring the carrier density and mobility in the wires. In the next phase we plan to reduce the backgate width and spacing to form electrically gated quantum dots and do coulomb blockade experiments."

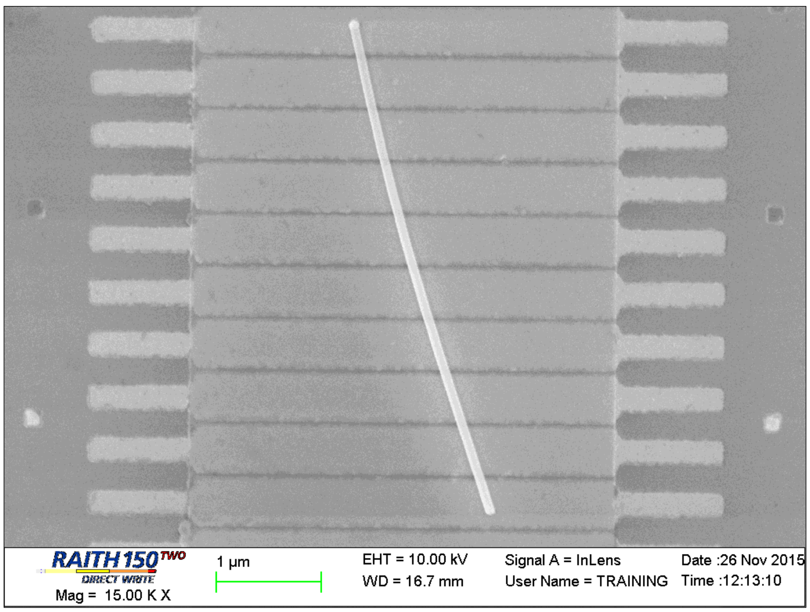


Figure 15:
Nanowire, pre-processing
(S. Gibson)

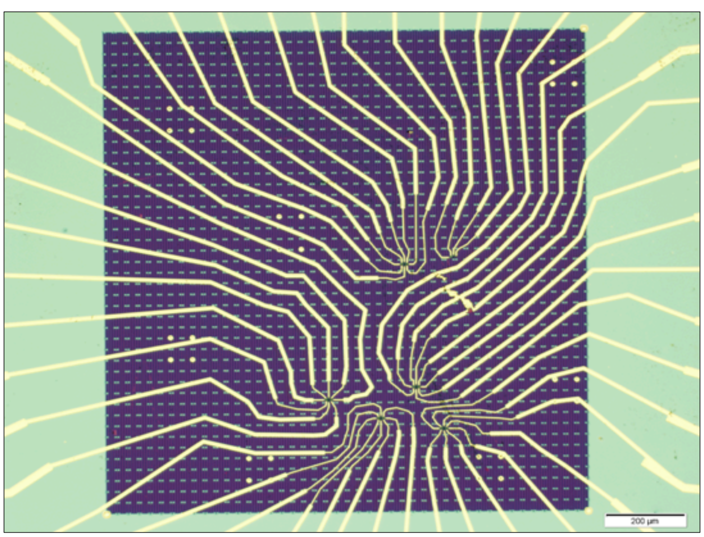


Figure 16: Nanowire FET device post lift-off (S. Gibson)

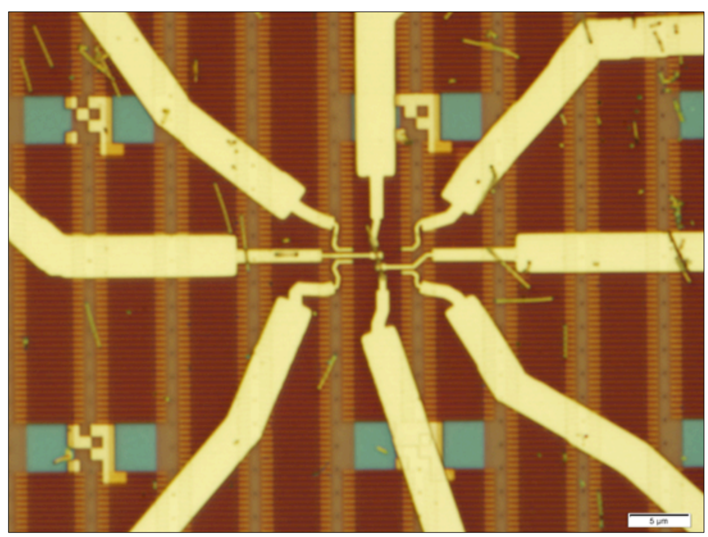


Figure 17: Nanowire FET device, single wire (S. Gibson)

GREG HOLLOWAY, PHD STUDENT, BAUGH GROUP (IQC)

The following images show a silicon MOS quantum dot. This work was undertaken by Greg Holloway in Prof. Baugh's group.

"The goal for this device is to top gate intrinsic Si using a MOS structure to create electrostatic quantum dots in the Si. This works by accumulating a layer of electrons at the Si/SiO_2 interface, then using local gates to create tunnel barriers, and in the right geometry a quantum dot. The structure shown here features two quantum dots in close proximity so we can use one to probe states in the other. The SEM images show the Al gates on top of the SiO_2 which were written with EBL, the size of the quantum dots is roughly 40 nm x 50 nm. An interesting engineering feature of these devices is that to prevent leakage between the overlapping gates we don't deposit an additional dielectric, but rather oxide the Al itself to create a very thin and robust insulating layer. This is achieved by exposing the Al to a weak oxygen plasma, in between depositing the two metal layers."

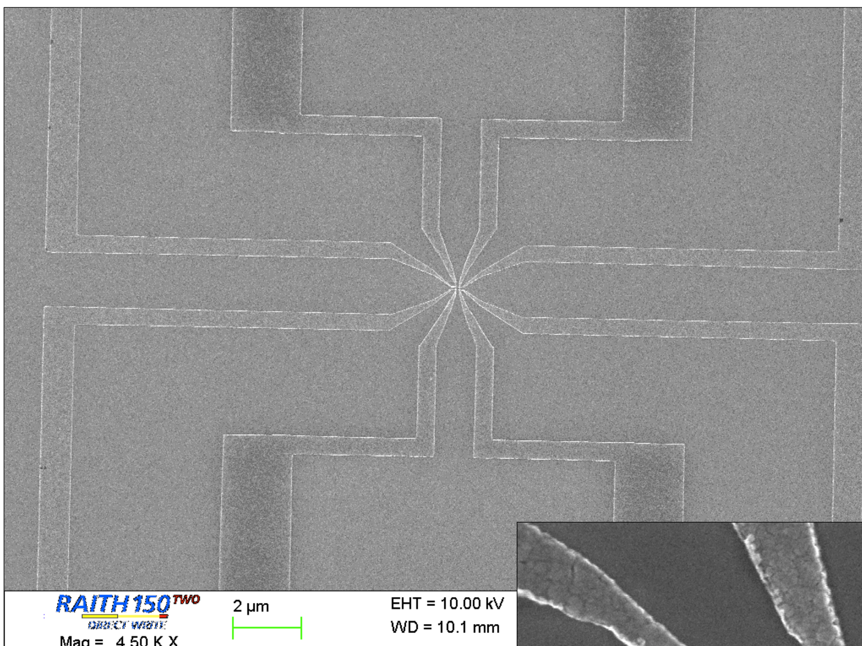


Figure 18: Si MOS Quantum Dot (G. Holloway)

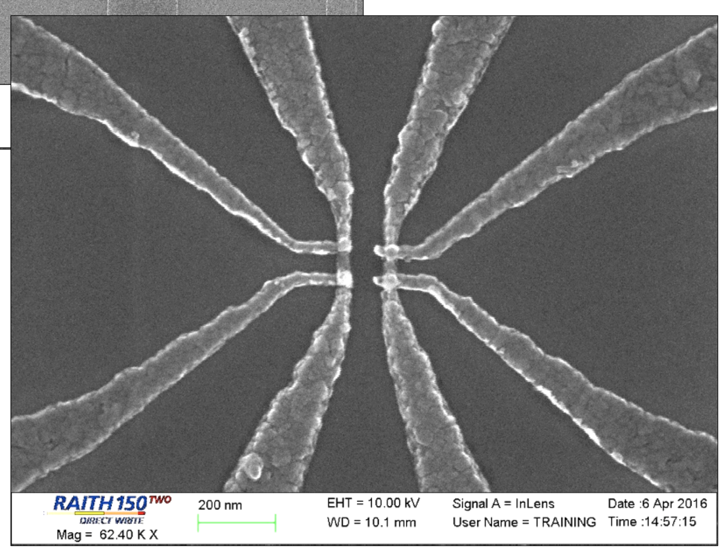


Figure 19: Zoomed in view of Si MOS Quantum Dot structure (G. Holloway)

MARIANTONI GROUP (IQC)

Work undertaken in Prof. Mariantoni's group.

" The image shows a 15 mm x 15 mm chip mounted in an aluminum sample holder. The chip comprises a set of three coplanar waveguide (CPW) transmission lines, each coupled to a number of CPW resonators. The resonators are made from a 100 nm aluminum thin film, which becomes superconducting when cooled below approximately -272 °C. The input and output ports of the transmission line are connected to control and measurement electronics by means of three-dimensional wires that reach the sample from above, making it possible to contact any point on the chip without wire bonds. We refer to this wiring system as the quantum socket. The quantum socket will allow the implementation of extensible quantum computing architecture comprising hundreds of quantum bits based on superconducting devices."

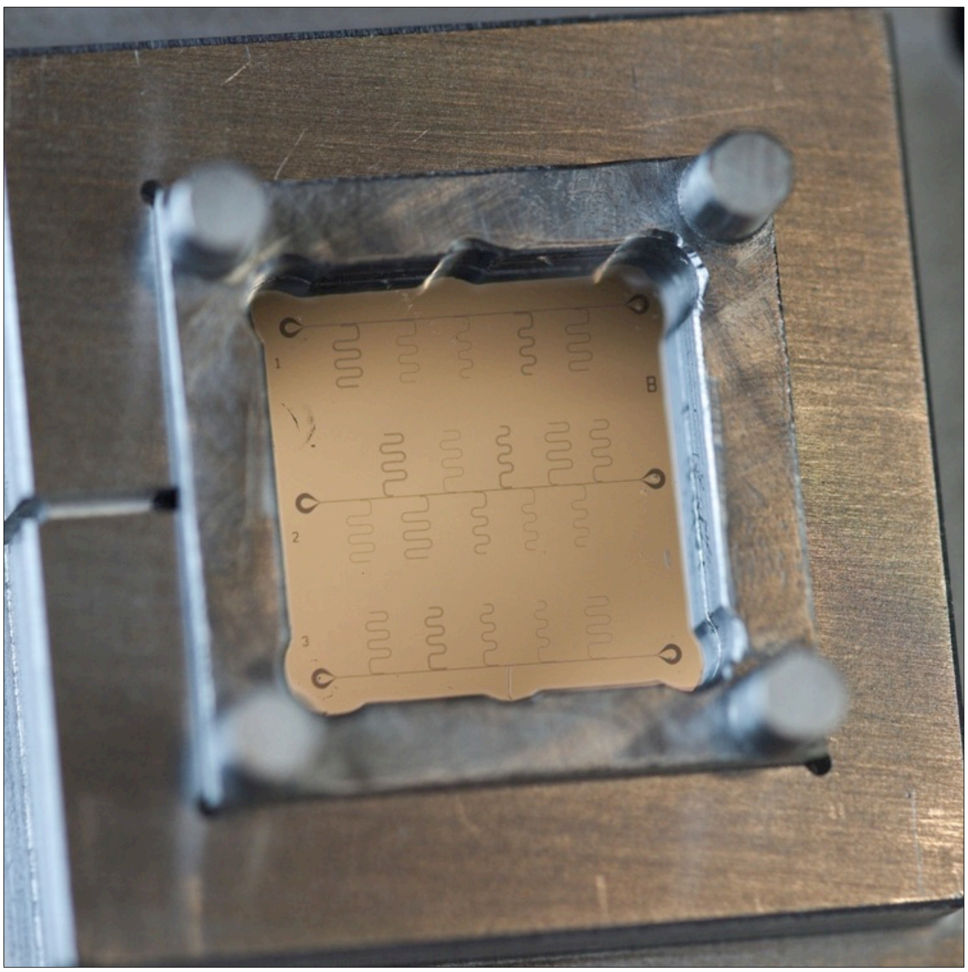


Figure 20: Quantum Socket

(J.H. Béjanin & M. Mariantoni)

6. EQUIPMENT BOOKINGS & TRENDS

Table 4 shows the annual trend of equipment hours invoiced since operations first began in November 2009 with the acquisition of the Raith 150TWO e-beam lithography system. A total of 7752 hours were invoiced in FY2015/16, a new record.

The number of hours invoiced in fiscal years 2013/14 and 2014/15 was lower than usual largely due to the reduced number of months of operation for both these years. In addition, operations in the Lazaridis Quantum-Nano Centre were slow to ramp up in September 2014 given the adoption of new access and training protocols. These were more rigorous than the procedures implemented in the temporary RAC1 cleanroom given the QNC facility's more stringent ISO 5 and ISO 6 certification levels. As has been the case since September 2014 the cleanroom behaviour and safety training programs include multiple online modules and quizzes which must be successfully completed by all members prior to being granted facility access. The training program remains in place to this day.

The prorated number of total equipment use hours for FY2014/15 is approximately 3000 whereas a total of 7752 hours of tool use were recorded over the course of FY205/16. This represents a substantial year-over-year growth of 259%.

As shown in the graph below, trends noted at the time of publication suggest that FY2016/17 equipment use will largely surpass the existing record by a factor of 40 to 50%.

Table 4: Total Equipment Hours Invoiced per Fiscal Year since 2009

2009/10	2010/11	2011/12	2012/13	2013/14*	2014/15*	2015/16	TOTAL
235	1073	3551	6153	3985	1984	7752	**16981**

*Fab in operation for only 7 of 12 months during FY2013/14 and for 8 of 12 months during FY2014/15

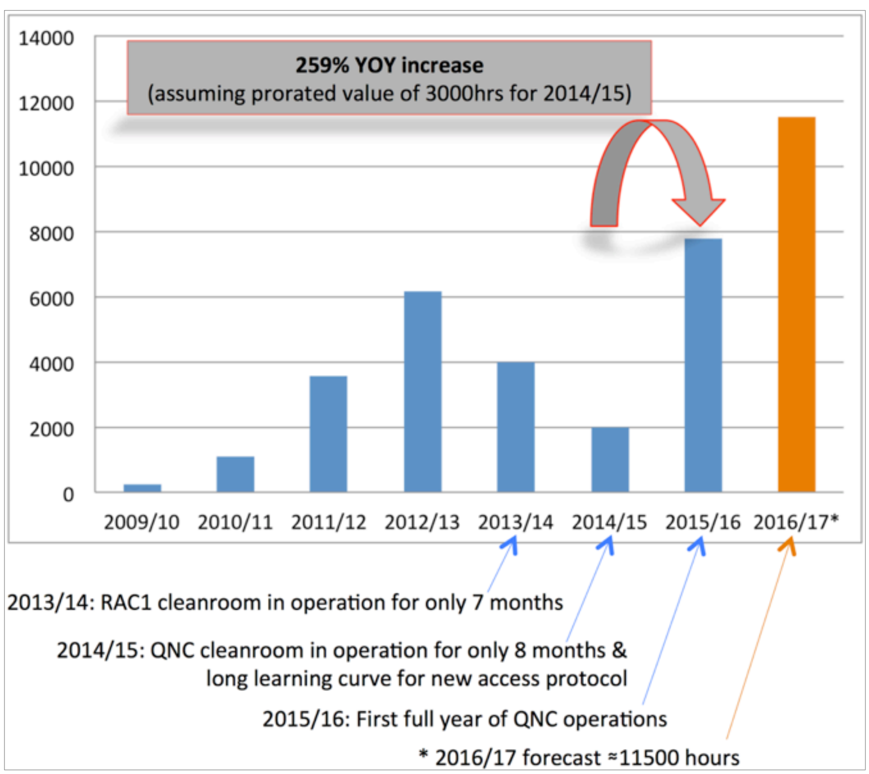
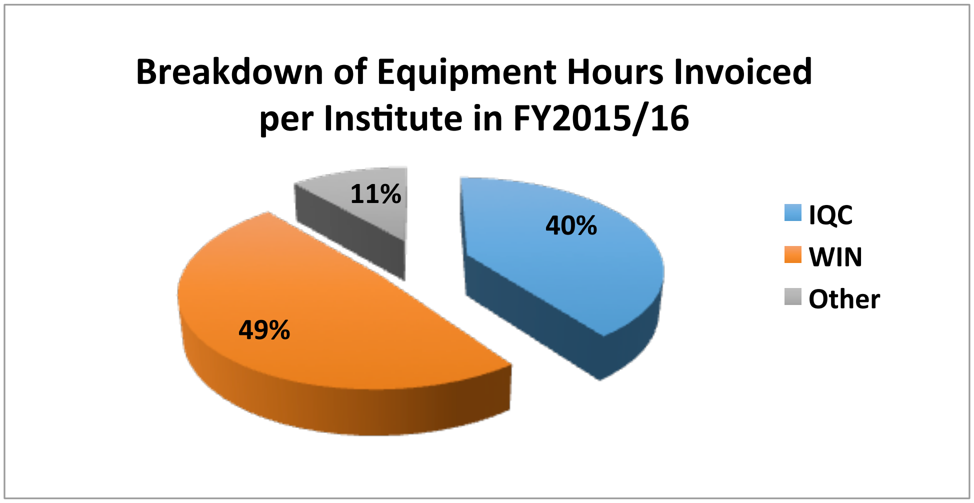


Table 5 shows the number of equipment hours invoiced per Principal Investigator over the course of FY2015/16.

Table 5: Equipment Hours Invoiced per Faculty Member in 2015/16 (Total of 7752)

Name	IQC	WIN	Other
Abdel-Rahman, Eihab			
Aitchison, Stewart			41
Aziz, Hany		1	
Bajcsy, Michal	789		
Ban, Dayan		913	
Baugh, Jonathan	867		
Budakian, Raffi	104		
Cory, David	441		
Cui, Bo		519	
Hodgson, Chad			22
Karim, Karim			
Knights, Andy			281
Laflamme, Raymond			
Lupascu, Adrian	30		
Maheshwari, Vivek			253
Majedi, Hamed		106	
Makarov, Vadim	17		
Mansour, Raafat		358	
Mariantoni, Matteo	306		
Mayer, Michael			138
Miao, Guo-Xing	92		
Nazar, Linda		20	
Pawliszyn, Janusz			
Perumal, Veeramani			5
Reimer, Michael	113		
Ren, Carolyn			
Safavi-Naeini, Safieddin		254	
Sciaini, German		405	
Saini, Simarjeet		329	
Teklemariam, Grum			145
Tsen, Wei	17		
Wang, Xiaosong		1	
Wasilewski, Zbig			
Wilson, Christopher	321		
Yavuz, Mustafa		534	
Yeow, John		330	
TOTAL	**3097**	**3770**	**885**



7. EXPENSES & REVENUES

Indirect costs continue to be shared equally by both institutes. Direct costs were paid for via a combination of the following funding sources:

- CFI-IOF funds from the original CFI grant (# 11544) which funded the construction and outfitting of the facility
- revenues generated from access fees charged to lab members
- funds provided by the University of Waterloo's *Office of the Provost*
- IQC's Industry Canada grant (*see Appendix D for details*)

7.1. INDIRECT COSTS

Table 6: Indirect Costs shared equally by IQC & WIN *

* These costs are not CFI-IOF admissible and are therefore equally borne by both institutes

Category	IQC	WIN
Salary & Benefits, Director	50%	50%
Salary & Benefits, Accounting Support ** ** 1 day per week	50%	50%
Salary & Benefits, Information Technology Support ** ** 1 day per week	50%	50%

7.2. DIRECT COSTS

A summary of the direct costs incurred over the course of FY2015/16 is presented in Table 7. A year-by-year financial summary (income & expenses) of fab operations since fiscal year 2011/12 is detailed in Appendix D. This year's total of $1,049M is 36% greater than the $771k in direct costs reported last year.

Salary costs increased by 26%. This is due in part to the fact that FY2015/16 represented the first full year of Matt Scott's contribution to the team, and due in part to Melissa Floyd having joined the team in October 2015. In addition, annual base salary increases consistent with UWaterloo Human Resources policies also contributed slightly to the growth of these costs.

Equipment service contract costs increased by 35%. This is explained by the fact that the previous year's cost for these contracts was lower than usual. Specifically, the FY2014/15 cost for the *Oxford Instruments* service contract was approximately 50% lower than initially planned due to a one-time discount. Oxford granted this discount due to their exceptional growth and corresponding inability to complete all the required preventive maintenance visits over the previous two years. The worsening CAD to USD exchange rate also impacted the overall cost of both the Oxford and Raith EBL service contracts in 2015/16.

The cost of general equipment and facility maintenance, repairs and cleanroom supplies increased by 53%. These variable costs are to a large extent directly related to facility use. A 53% increase in these particular costs is considered reasonable given the substantial 259% increase in equipment use.

Bulk nitrogen consumption costs grew by 49% to $154k with respect to last year's cost estimate of $103k. While difficult to pinpoint specific causes for this increase the following four factors likely all contributed to the large year over year variance:

- 259% increase in equipment use
- Commissioning of several additional furnace processes which are relatively large consumers of bulk nitrogen
- Issue with Oxford ALD roughing pump control sequence caused it to consume more nitrogen gas for its purge function than required
- Last year's consumption cost estimate likely not well aligned with actual consumption figures for the year. Ie., last year's estimate was likely too conservative.

Table 7: Breakdown of Direct Costs - FY2015/16

SALARY & BENEFITS			
	Sub-Total:	$460,623	44%
SUPPLIES, MAINTENANCE & EQUIPMENT			
Equipment service contracts (4 Oxfords & Raith EBL)		$218,780	21%
Supplies, maintenance & general repairs		$216,421	20%
	Sub-Total:	$435,201	
OTHER			
Bulk nitrogen supply (paid for by *VP Academic & Provost*)			
	Sub-Total:	$153,830	15%
	GRAND-TOTAL:	**$1,049,654**	

7.3. REVENUES

Monthly invoices were issued to each registered Principal Investigator over the course of the entire fiscal year. The total amount invoiced for 2015/16 is $330,177. This represents a greater than fourfold increase over the previous year's total of $80,860. Facility access fees were collected throughout the reporting period as a function of the fee schedule published on the public portal of the fab website: https://fab.qnc.uwaterloo.ca/data/access/fees/doc

A summary of total fab charges invoiced per Principal Investigator over the period May 1, 2015 to April 30, 2016 is included in Appendix E.

This year's revenues were used to cover a portion of the facility's direct operating costs detailed in section 7.2. All revenues generated from the collection of facility access fees continue to be applied, in their entirety, to fab operations.

The remaining balance of the CFI-IOF funds granted against CFI project # 11544 continues to be dedicated to the operations of the Quantum NanoFab and the QNC Metrology Lab, both of which are IQC & WIN jointly operated facilities. These funds remain earmarked for the salaries of technical staff dedicated to the operation & maintenance of both core facilities.

8. ACCESS FEES FOR 2016/17

Access fees in effect for FY2016/17 remain consistent with the rates first established in September 2014. These are listed in Appendix F. Access fees remain highly subsidized by:

- IQC
- WIN
- University of Waterloo
- CFI-IOF operating fund, project # 11544

As has been the case since temporary operations first began in the RAC1 cleanroom in November 2009, a single access fee structure remains in place for all academic members, regardless of affiliation (IQC, WIN or other academic), and regardless of PI status (junior or senior faculty). Industrial access rates remain fixed at 3X the academic rates.

9. KEY OBJECTIVES & ACTIVITIES FOR FY2016/17

Multiple Fab Team objectives have been identified for FY2016/17:

People, Finances & General operations

- Hire qualified individual into new *Electron Beam Lithography Senior Scientist* position, to be created by mid 2016. This individual will dedicate their time to developing & maintaining advanced e-beam lithography process technologies for the facility's 30kV & 100kV systems, and will also offer general UV & e-beam litho support to the entire membership. Creation of this new position received the approvals of Raymond Laflamme, Executive Director of IQC, George Dixon, Vice-President University Research, and Ian Orchard, Vice-President Academic & Provost.
- Hire Co-op students on an ongoing basis with an aim of expanding facility hours of operation.
- Commence using new *TRAX* supplies ordering system as of May 1, 2016. This will lay the groundwork for quantifying cost of operations on a per-tool basis going forward.
- Contribute $50k towards the 7% cleanroom fit-out project cost overrun (see section 4.2.3 in the special *2013/13 to 2013/14 Annual Report*).

Lab Member Experience & Efficiency, Outreach

- Establish an in depth 100kV e-beam lithography training program with a primary aim of helping interested lab members make exceptionally good use of the advanced JEOL JBX-6300FS EBL system.
- Roll out and execute the JEOL training program. Focus on getting all initial interested members (14 people to start) fully trained and qualified for independent system use as quickly as reasonably possible.

- Once Co-op students have been hired establish & roll out a new facility access policy geared towards expanding facility weekday hours of operation (phase 1) and weekend hours of operation (phase 2).
- Accommodate WIN request for high level nanofab process training for *University of Bristol* guests (July 2016) as well as ongoing IQC fab access request for *USEQIP* participants (June 2016).
- Accommodate cleanroom tour requests (as required).
- Talks & updates:
    - WIN Board of Directors update (as required)
    - IQC Board of Directors update (as required)
    - Others (as required)

Lab Equipment

- Commission last remaining tools including Tystar LPCVD polysilicon tube, Tystar LPCVD LTO tube, both Brewer spin coat & bake hoods and the Westbond semi-automatic wire bonder.
- Commission last remaining process gases ($SiCl_4$, HBr, Methylsilane, Acetylene) as a function of lab member process requests.
- Negotiate terms of ongoing annual service contract for JEOL EBL system before its March 2017 installation anniversary.
- Define specifications for new aluminum angle, ultra high vacuum evaporator system dedicated to Josephson junction formation in support of multiple quantum research efforts. Proceed with public tender over the course of summer 2016 and place an order before fall 2016. System acquisition and installation will be funded by IQC. The new tool will be accessible to the Quantum NanoFab's entire membership.

Facilities

- Acquire new particle counter to replace existing failed unit. Reinstate regular particle count measurements & data logging as required to maintain ISO 5 and ISO 6 cleanroom certification.
- Improve methodology used for tracking routine infrastructure data such as gas cylinder pressures, process gas delivery pressures, water pressures, etc., via the use of an electronic interface for data entry into a central database. Database will allow querying & graphing of trends which can be beneficial during troubleshooting activities. Digitization of these infrastructure parameters may also serve to automatically flag possible issues or the need for gas cylinder replacements (for example) thus minimizing the risk of negative impacts to operations and member research efforts.

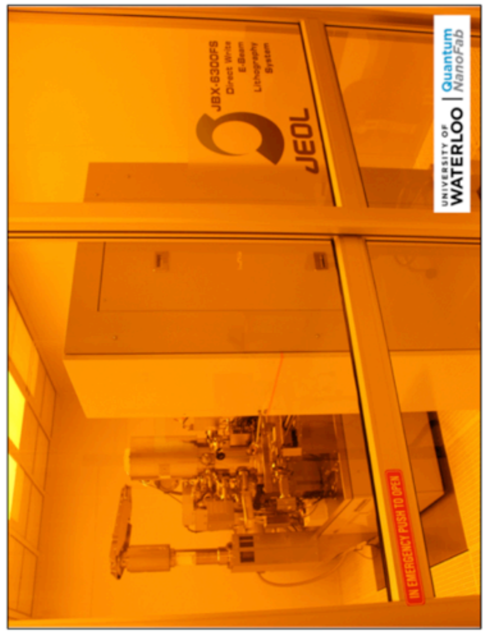
Submitted by: Vito Logiudice MASc, P.Eng.
Director, Quantum NanoFab
December 9, 2016

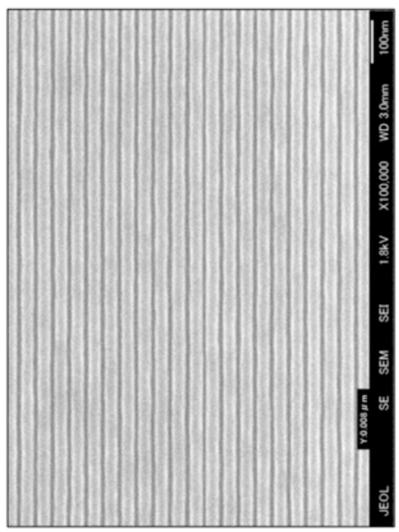
APPENDIX A: SUMMARY OF TOOLS INTERLOCKED WITH BADGER (APRIL 2016)

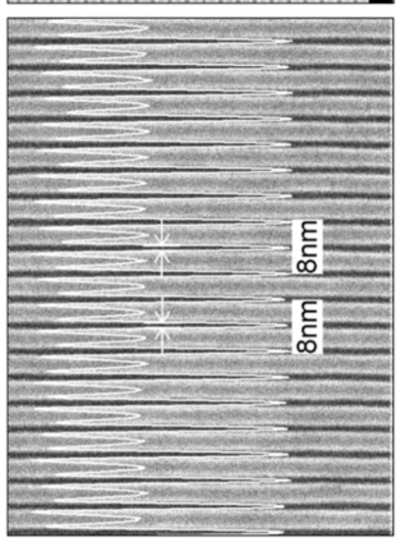
Tool Type	Tool Name	Tool Interlocked with Badger?
E-beam Lithography	JEOL-EBL	yes
E-beam Lithography	RAITH 150TWO	yes
Mask Aligner	SUSS-MA6 front/back	yes
HMDS oven	YES-HMDS	yes
semi-auto spin/bake	BREWER-UVspinbake	not yet commissioned
PR spin/bake station	BREWER-Ebeamspinbake	not yet commissioned
PR spin/bake station	REYNOLDSTECH-twincoater	yes
atmospheric oven	FISHER-oven	yes
E-beam evaporator	INTLVAC-Ebeam	yes
ALD & PECVD	OXFORD-ALD/PECVD cluster	yes
Automated sputter	PLASSYS-Nb sputter	staff only (password protected)
oxidation/anneal furnace	TYSTAR1-atm	staff only (password protected)
LPCVD Nitride furnace	TYSTAR2-nitride	staff only (password protected)
LPCVD Poly furnace	TYSTAR3-Poly & SiC	staff only (password protected)
LPCVD LTO furnace	TYSTAR4-LTO	staff only (password protected)
Sputter	AJA-2-chamb, loadlocked	yes
atmospheric RTA/RTP	ALLWIN-RTP	yes
ICPRIE - Cl chemistries	OXFORD-metalRIE	yes
ICPRIE - F chemistries	OXFORD-Si deep RIE	yes
Ashing RIE	YES-ash	yes
Ion mill 6" wafer	AJA-ionmill	yes
Cont. ang. goniometer	RAMEHART-contactangle	
LWD opt microscope	OLYMPUS-scope3	yes
Dicing saw	DISCO-saw	yes
wirebond pull tester	WESTBOND-pulltest	
Semi-auto wirebond	WESTBOND-wirebond1	yes
multimode wirebond	WESTBOND-wirebond2	yes
Flip chip die bonder	TRESKY-diebond	yes
diamond scribe tool	OEG-scriber	
epoxy dispenser robot	NORDSON-epoxy	
H plasma cleaner	LFC-plasmaclean	
epoxy cure oven	Cureoven	
wafer cleaner	ULTRON-cleaner	
reflectometer	FILMETRICS-F40	yes
reflectometer -auto	FILMETRICS-F50	yes
wafer microscope	OLYMPUS-scope1	yes
wafer microscope	OLYMPUS-scope2	yes
stylus profilometer	VEECO-profilometer	yes
auto. 4-point probe	CDE-4pp	
stress meas. tool	TOHO-stress	yes
ellipsometer	WOOLLAM-ellip	yes
Wetbench - Acids	ACIDBASEnonHF	yes
Wetbench - HF	HFACID	yes
Wetbench - solvents	SOLVENT1	yes
Wetbench - solvents	SOLVENT2	yes
Wetbench - RCA clean	RCACLEAN	yes
Wetbench - KOH	REYNOLDSTECH-bulkSi	yes
Wetbench - Piranha	PIRANHA	yes
Wetbench - UV dev	DEVELOPUV	yes
Wetbench - EBL dev	DEVELOPEBL	yes

APPENDIX B: JEOL JBX-6300FS 100KV EBL SITE ACCEPTANCE RESULTS

	ITEMS		Conditions	Measurements	Specification	Results	
						X	Y
1	Minimum line width	Measurement at field center	Acc. Volt: 100kV	At field center	8nm or less	8.0 nm	8.0 nm
						Min	Max
2	Mask writing performance	1) Field stitching accuracy	Acc. Volt: 100kV	Pattern position measurement (LEICA IPRO)	+/- 20nm or less	-8.5 nm	8.3 nm
						Min	Max
3	Direct writing performance	1) EB-EB overlay accuracy	Acc. Volt: 100kV	Pattern position measurement (LEICA IPRO)	+/- 20nm or less	-2.2 nm	9.2 nm
						Min	Max
		2) Field stitching accuracy			+/- 20nm or less	-6.2 nm	9.2 nm







APPENDIX C: NANOFABRICATION RESEARCH PROJECT TITLES SINCE SEPT 2014

1. Abdel-Rahman – Frequency modulated MEMS gyroscope
2. Aktary "Applied Nanotools Inc." – Nanofabrication of optics
3. Aitchison "University of Toronto" – Multi waveguide integration
4. Aziz – Ellipsometry of organic films
5. Bajcsy – Chip-scale platform
6. Bajcsy – High-efficiency multi-layer diffraction gratings for atom cooling on a chip
7. Bajcsy – On-chip RF resonator for metastable xenon generation
8. Bajcsy – Nanophotonic structures for quantum optics on a chip
9. Ban – Quantum cascade laser
10. Baugh – InSb quantum well based devices
11. Baugh – Graphene exfoliation and transfer
12. Baugh – Fabrication of Si and nanowire based quantum dots
13. Baugh – InAs nanowire and silicon 2deg devices
14. Baugh – Superconductor-semiconductor devices for QIP
15. Baugh – Sidemse project
16. Baugh – Carbon nanotube devices
17. Budakian – Growth of Si nanowires
18. Budakian – Silver constrictions for nano-MRI
19. Budakian – Force-detected nanoMRI using SiNW resonators
20. Carson – Bragg reflector
21. Cory – NV diamond chemical sensor
22. Cory – Diamond based quantum processors
23. Cory – Fabrication of spintronic components
24. Cory – Optical lithography of superconducting electronics
25. Cui – Development of silicon etching recipe
26. Cui – Fabrication of metal nanostructure for nano-photonic application
27. Cui – Sensor fabrication

28. Cui – Profile control of silicon etching
29. Cui – Fabrication of AFM tip
30. Cui – Fabrication of THz antenna
31. Cui – Deep etching of Si structures
32. Hodgson "Transonic Scisense" – Pressure sensor singulation
33. Karim – Digital x-ray imaging
34. Kinghts "Ranovus" – Development of silicon photonic circuits
35. Lupascu – Superconducting quantum devices
36. Lupascu – Superconducting qubits
37. Mayer – Packaging process research
38. Mayer – Flipchip & plasma cleaner
39. Mayer – Reliability of flip-chip bumps with composite solder alloy
40. Mehashwari "Medella Health" – Miniaturized glucose sensor
41. Maheshwari "Medella Health" – Creating characteristic nanoscale electrodes
42. Maheshwari "Medella Health" – Smart contact lens integration
43. Maheshwari "Medella Health" – Plasmonic MEMS
44. Majedi – Nanowire quantum dot
45. Makarov – Photographing samples using optical microscopes
46. Mansour – AFM project
47. Mansour – MEMS
48. Mansour – VO_2 deposition
49. Mansour – CMOS MEMS mmwave switches
50. Mariantoni – Superconducting quantum circuits
51. Mariantoni – Superconducting qubits
52. Miao – Josephson junctions with magnetic insulators
53. Miao – Fabrication of MgB_2 Josephson junctions
54. Miao – Tunnel junction fabrication
55. Miao – Graphene spintronics

56. Nazar – Patterning solid electrolyte
57. Nieva – Protein biomems sensor
58. Pawliszyn – Plastic SPME meshes for dart applications
59. Perumal "Redlen Technologies" – Material surface modification
60. Ren – Carbon dioxide capture and storage impact
61. Reimer – Tunable quantum light sources
62. Reimer – Nanowire photonic devices
63. Safavi-Naeini – Graphene based optical bistable switch
64. Safavi-Naeini – Terahertz silicon waveguide
65. Safavi-Naeini – Dielectric antenna and passives for sub THz applications
66. Safavi-Naeini – Graphene travelling wave amplifier
67. Safavi-Naeini – Graphene nano photonics
68. Safavi-Naeini – Silicon based nanostructure materials
69. Safavi-Naeini – Si ion on glass waveguide
70. Saini – Nanophotonics fabrication and chips
71. Sciaini – Nanocell
72. Sciaini – Nanofluidic cell fabrication
73. Sciaini – Nanofluidic cell for electron diffraction
74. Teklemariam "High Q Technologies" – Fabrication of niobium resonators
75. Tsen – Magneto transport in 2D superconductors
76. Wang – Characterization of metal-carbonyl complexes and polymers
77. Wasilewski – III-V semiconductor structures for PCA
78. Wilson – Lockheed QT
79. Wilson – Quantum simulations
80. Yavuz – Ultra fast graphene actuator
81. Yavuz – Quantum Dot Fabrication
82. Yavuz – Graphene field effect transistor production
83. Yavuz – Fabrication of IM diodes

84. Yavuz – Graphene sensor
85. Yavuz – Graphene based nano biomarkers for cancer diagnosis
86. Yavuz – Nano-photonics system for enhanced light-matter interactions
87. Yavuz – Graphene electronics transistor
88. Yavuz – FET-sensor
89. Yavuz – Production and characterization of graphene biosensors
90. Yeow – X-ray source based on carbon nanotube field emission

APPENDIX D: YEAR-BY-YEAR FINANCIAL SUMMARY OF FAB OPERATIONS

Annual Report - Quantum NanoFab Financial Summary

	2012	2013	2014	2015	2016	TOTAL
INVOICING						
Invoice Total Value for Year	$86,583	$157,915	$111,333	$80,860	$330,177	**$766,868**
Funds Received for Year (into Fund 100)	$66,638	$120,084	$106,072	$59,806	$278,535	**$631,135**
Number of Invoices Issued to Users	86	129	90	86	249	**640**
SALARY EXPENSES						
Technician Salary and Benefits on Industry Canada	80,610	247,500	181,313	204,799	383,548	1,097,770
Technician Salary and Benefits on CFI-IOF (Fund 105) (no Metrology technicians)	142,035	26,613	106,901	158,639	49,161	483,349
CleanRoom Salary and Benefits on Operating (Fund 100)			2,095	2,274	27,914	32,283
TOTAL	**222,645**	**274,113**	**290,309**	**365,712**	**460,623**	**1,613,402**
SUPPLIES, MAINTENANCE AND EQUIPMENT EXPENSES						
Supplies/Equipment/Maintenance on Industry Canada	34,935	28,546	0	0		63,481
Supplies/Equipment/Maintenance on CFI-IOF (Fund 105)	34,232	65,827	88,654	160,789	217,902	567,404
Supplies/Equipment/Maintenance on Operating (Fund 100)			397,828	141,590	217,299	756,717
TOTAL	**69,167**	**94,373**	**486,482**	**302,379**	**435,201**	**1,387,601**
PRAXAIR EXPENSES						
Praxair on Industry Canada	16,113	14,351	10,206	0	0	40,670
Praxair on CFI-IOF (Fund 105)	16,113	13,547	10,287	0	0	39,947
Office of VP Academic & Provost			0	103,000	153,830	256,830
TOTAL	**32,226**	**27,898**	**20,494**	**103,000**	**153,830**	**337,448**
GRAND TOTAL	**324,038**	**396,384**	**797,285**	**771,091**	**1,049,653**	**3,338,451**

SPENDING BY GRANT	**2012**	**2013**	**2014**	**2015**	**2016**	**TOTAL**
Spending on Industry Canada	131,658	290,397	191,519	204,799	383,548	**1,201,921**
Spending on CFI-IOF (fund 105) no metrology nor director salary	192,380	105,987	205,842	319,428	267,063	**1,090,700**
Spending on Operating (Fund 100)	0	0	399,923	143,864	245,212	**788,999**
Office of VP Academic & Provost	0	0	0	103,000	153,830	**256,830**
GRAND TOTAL	**324,038**	**396,384**	**797,285**	**771,091**	**1,049,653**	**3,338,451**

***** Salaries do NOT include metrology lab technician salaries paid on CFI-IOF nor director salary and benefits***

APPENDIX E: FAB FEES INVOICED PER PRINCIPAL INVESTIGATOR IN 2015/16

Name	IQC	WIN	Other
Abdel-Rahman, Eihab			
Aitchison, Stewart (U of Toronto)			$1,723
Aziz, Hany		$59	
Bajcsy, Michal	$29,359		
Ban, Dayan		$30,047	
Baugh, Jonathan	$33,721		
Budakian, Raffi	$3,776		
Cory, David	$17,565		
Cui, Bo		$21,771	
Hodgson, Chad (Transonic Scisence)			$2,742
Karim, Karim			
Knights, Andy (Ranovus)			$36,778
Laflamme, Raymond			
Lupascu, Adrian	$939		
Maheshwari, Vivek (VELOCITY)			$9,411
Majedi, Hamed		$4,585	
Makarov, Vadim	$343		
Mansour, Raafat		$14,752	
Mariantoni, Matteo	$10,108		
Mayer, Michael (UW Mech Eng)			$5,007
Miao, Guo-Xing	$3,786		
Nazar, Linda		$630	
Pawliszyn, Janusz			
Perumal, Veeramani (Redlen Technologies)			$692
Reimer, Michael	$4,586		
Ren, Carolyn			
Safavi-Naeini, Safieddin (UW Elec Eng)			$9,845
Sciaini, German		$14,493	
Saini, Simarjeet		$14,561	
Teklemariam, Grum (High Q Technologies)			$13,665
Tsen, Wei	$648		
Wang, Xiaosong		$32	
Wasilewski, Zbig			
Wilson, Christopher	$11,049		
Yavuz, Mustafa		$21,874	
Yeow, John		$13,353	
TOTAL	**$115,880**	**$136,157**	**$78,140**

UNIVERSITY OF WATERLOO | Quantum NanoFab

Facility Access Fees

Tool Type	Tool Name	Academic Rate	Industrial Rate
E-beam Lithography	RAITH 150TWO	$ 60	$ 180
Mask Aligner	SUSS-MA6 front/back	$ 35	$ 105
HMDS oven	YES-HMDS	$ 25	$ 75
semi-auto spin/bake	BREWER-UVspinbake	$ 30	$ 90
PR spin/bake station	BREWER-Ebeamspinbake	$ 35	$ 105
PR spin/bake station	REYNOLDSTECH-twincoater	$ 25	$ 75
atmospheric oven	FISHER-oven	$ 15	$ 45
E-beam evaporator	INTLVAC-Ebeam	$ 35	$ 105
ALD & PECVD	OXFORD-ALD/PECVD cluster	$ 50	$ 150
Automated sputter	PLASSYS-Nb sputter	$ 40	$ 120
oxidation/anneal furnace	TYSTAR1-atm	$ 40	$ 120
LPCVD Nitride furnace	TYSTAR2-nitride	$ 45	$ 135
LPCVD Poly furnace	TYSTAR3-Poly & SiC	$ 45	$ 135
LPCVD LTO furnace	TYSTAR4-LTO	$ 45	$ 135
Sputter	AJA-2-chamb, loadlocked	$ 40	$ 120
atmospheric RTA/RTP	ALLWIN-RTP	$ 40	$ 120
ICPRIE - Cl chemistries	OXFORD-metalRIE	$ 45	$ 135
ICPRIE - F chemistries	OXFORD-Si deep RIE	$ 45	$ 135
Ashing RIE	YES-ash	$ 25	$ 75
Ion mill 6" wafer	AJA-ionmill	$ 45	$ 135
Cont. ang. goniometer	RAMEHART-contactangle	$ 15	$ 45
LWD opt microscope	OLYMPUS-scope3	$ 15	$ 45
Dicing saw	DISCO-saw	$ 40	$ 120
wirebond pull tester	WESTBOND-pulltest	$ 10	$ 30
Semi-auto wirebond	WESTBOND-wirebond1	$ 40	$ 120
multimode wirebond	WESTBOND-wirebond2	$ 40	$ 120
Flip chip die bonder	TRESKY-diebond	$ 45	$ 135
diamond scribe tool	OEG-scriber	$ 30	$ 90
epoxy dispenser robot	NORDSON-epoxy	$ 15	$ 45
H plasma cleaner	LFC-plasmaclean	$ 30	$ 90
epoxy cure oven	Cureoven	$ 15	$ 45
wafer cleaner	ULTRON-cleaner	$ 20	$ 60
reflectometer	FILMETRICS-F40	$ 10	$ 30
reflectometer -auto	FILMETRICS-F50	$ 10	$ 30
wafer microscope	OLYMPUS-scope1	$ 20	$ 60
wafer microscope	OLYMPUS-scope2	$ 20	$ 60

QuantumNanoFabFees_rev_7.xlsx Rates in effect as of September 1, 2014 1/2

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Facility Access Fees

Tool Type	Tool Name	Academic Rate	Industrial Rate
stylus profilometer	VEECO-profilometer	$ 20	$ 60
auto. 4-point probe	CDE-4pp	$ 20	$ 60
stress meas. tool	TOHO-stress	$ 30	$ 90
ellipsometer	WOOLLAM-ellip	$ 40	$ 120
Wetbench - Acids	ACIDBASEnonHF	$ 25	$ 75
Wetbench - HF	HFACID	$ 25	$ 75
Wetbench - solvents	SOLVENT1	$ 25	$ 75
Wetbench - solvents	SOLVENT2	$ 25	$ 75
Wetbench - RCA clean	RCACLEAN	$ 25	$ 75
Wetbench - KOH	REYNOLDSTECH-bulkSi	$ 40	$ 120
Wetbench - Piranha	PIRANHA	$ 25	$ 75
Wetbench - UV dev	DEVELOPUV	$ 25	$ 75
Wetbench - EBL dev	DEVELOPEBL	$ 25	$ 75

Additional Fees:

1) For Academic Users, cleanroom consumables costs are recovered via a charge of $1.84 per each equipment "enable" within Badger.

   For Industrial Users, the cleanroom consumables fee is $5.52 per equipment enable.

2) For Academic Users, equipment training is completed by facility staff and is charged at $25 per hour.
   For Industrial Users, equipment training is charged at $75 per hour.

3) For Academic Users, general support provided by facility staff is charged at $50 per hour.
   For Industrial Users, general support is charged at $150 per hour.

QuantumNanoFabFees_rev_7.xlsx   Rates in effect as of September 1, 2014   2/2