WORKSHOP ON QUANTUM ENGINEERING INFRASTRUCTURE
FINAL REPORT

EXECUTIVE SUMMARY

The Workshop on Quantum Engineering Infrastructure (WQEI) was held *via* Zoom webinar from April 13-15, 2021. The workshop was sponsored by the National Science Foundation (NSF), and had two primary goals.

Goal 1 had the objective of informing the community of quantum researchers funded by the NSF as to how their projects can be supported by the National Nanotechnology Coordinated Infrastructure (NNCI). This goal was put in place to ensure the current facility infrastructure can best be utilized to enable new and ongoing projects. To help meet this short-term goal, a series of presentations were given by the site directors of several NNCI nodes, where they highlighted their quantum engineering capabilities. Presentations by experts on various aspects of quantum technology also helped to provide insights into the specific requirements for each technology.

Goal 2 had the objective of informing a strategic vision for the future of quantum fabrication infrastructure, and how shared national resources can best be positioned to meet the needs of quantum engineered systems. To address this longer-term goal, a series of breakout sessions were organized, where the participants discussed the broader infrastructure needs for quantum science and engineering research.

The workshop had 412 registered attendees in total with most from US universities, but with other attendees from government, industry, national labs and foreign universities.

A series of conclusions and recommendations were formulated. These conclusions are summarized briefly below, and much more extensive details are provided in the full report.

1) The NNCI currently has some degree of infrastructure for supporting quantum engineering and science research.
2) Quantum fabrication infrastructure needs are complicated by the vastly different nature of quantum computing and communication platforms, with some being more mature, and others still at the most basic research level. Quantum processing infrastructure therefore must strike a balance between the competing needs of these differing technological platforms.
3) A need exists to provide researchers access to more mature quantum processing platforms.
4) Improved access to key materials is needed. These include materials such as diamond, isotopically pure materials, Si/SiGe heterostructures, and others.
5) Mechanisms for maintaining and propagating key quantum-related process knowledge within the NNCI community is needed. While the NNCI does provide mechanisms for sharing process knowledge among staff, improvements can be made. Possible mechanisms include development of an NNCI “fellows” program to transfer faculty-supported researcher process knowledge to permanent process staff. Improved databases and web-based knowledge sharing is also needed.
6) Characterization at both the device and materials level is a key component of quantum infrastructure and cannot be ignored. Dilution refrigerator access is a particular bottleneck as is characterization techniques such as high-resolution SIMS. Improved characterization infrastructure could improve research productivity by reducing cycle times between fabrication and measurement.

1. Workshop Date and Locations

The workshop was held via Zoom webinar on three consecutive days from April 13-15, 2021.

2. Organizing Committee

The organizing committee was as follows:

- Steven Koester (University of Minnesota) (Conference, Session chair, Breakout moderator)
- Vlad Pribiag (University of Minnesota) (Session chair, Breakout moderator)
- David Goldhaber-Gordon (Stanford University) (Session chair, and Breakout moderator)
- Andrew Cleland (University of Chicago) (Breakout moderator)
- Mo Li (University of Washington) (Session chair, Breakout moderator)
- Arka Majumdar (University of Washington) (Session chair)
- Christopher Kemper Ober (Cornell University)
- Maude Cuchiara (North Carolina State University)
- Debra Senesky (Stanford University)
- Jelena Vuckovic (Stanford University)
- Robert Westervelt (Harvard University)
- Amir Hossein Safavi-Naeini (Stanford University)
- Karl Bohringer (University of Washington)
- Maria Huffman (University of Washington)
- Oliver Brand (Georgia Institute of Technology)
- David Gottfried (Georgia Institute of Technology)
- Trevor Thornton (Arizona State University)
- David Ferry (Arizona State University)
- Ines Mantano (Northern Arizona University)
- Vinayak Dravid (Northwestern University)
- Christian Binek (University of Nebraska)

3. Workshop Program and Format

The final conference program is shown below. The workshop was a 3-day event, with each session limited to ~ 5 hours to minimize "Zoom fatigue." The Cornell Nanoscale Facility (CNF) staff acted as conference hosts, and hosted the conference website, ran the Zoom webinar and collected registrations.

The workshop speakers and breakout session panelists were by invitation only. The invited speakers were chosen by topical area, so that as many relevant aspects of quantum information science and engineering can be covered as possible. However, some important areas were omitted due to time considerations, such as cold atom qubits and quantum sensing.

At the beginning of each session, the nodes of the NNCI presented were first provide a presentation on their node's quantum engineering capabilities. Each day ended with a breakout session, where a specific topic was discussed regarding quantum engineering infrastructure, reflecting upon the day's talks, and a short summary presentation by the moderator was given afterward. Organizing committee members acted as session chairs and breakout moderators.

Time (EDT)	DAY 1 Tuesday, 4/13	DAY 2 Wednesday, 4/14	DAY 3 Thursday, 4/15
12:00 PM	Welcome, **Steven Koester** *U Minnesota*	Welcome, **Steven Koester** *U Minnesota*	Welcome, **Steven Koester** *U Minnesota*
12:05 PM	Welcome, **Dawn Tilbury**, *NSF*	Intro to NQCO, **Alex Cronin**, *NQCO*	NNCI node presentations: *Minnesota, Cornell, Harvard, and Nebraska*
12:10 PM	Intro to NNCI program, **Lawrence Goldberg**, *NSF*	NNCI node presentations: *Stanford, U Washington, NC State, and Montana State*	
12:15 PM	Overview of NNCI program, **Oliver Brand**, *Ga Tech*		
12:35 PM	NSF Center for Quantum Networks, **Saikat Guha**, *U Arizona*	NSF Quantum Foundry**, Ania Bleszynski Jayich**, *UCSB*	DOE Quantum Science Center, **David Dean**, *ORNL* (starting at 12:30 PM)
1:05 PM	*Break*	*Break*	*Break (starting at 1:00 PM)*
1:15 PM	Superconducting Qubits 1, **David Schuster**, *U Chicago*	Color Centers & Optics 1, **Jelena Vuckovic**, *Stanford U*	Topological Qubits 1, **Chris Palmstrøm**, *UCSB*
1:45 PM	Superconducting Qubits 2, **Will Oliver**, *MIT-LL*	Color Centers & Optics 2**, Kai-Mei Fu**, *U Washington*	Topological Qubits 2, **Amir Yacoby**, *Harvard U*
2:15 PM	*Break*	*Break*	*Break*
2:30 PM	Trapped Ions 1, **Kenneth Brown**, *Duke U*	Color Centers & Optics 3, **Dirk Englund**, *MIT*	Spin Qubits 1 , **Mark Eriksson**, *UW-Madison*
3:00 PM	Trapped Ions 2, **Susan Clark**, *Sandia National Labs*	Color Centers & Optics 4, **Marko Lončar**, *Harvard U*	Spin Qubits 2, **Jason Petta**, *Princeton U*
3:30 PM	Breakout 1, SC Qubit Infrastructure Breakout 2, Trapped Ion Infrastructure	Breakout, Color Centers & Optics Infrastructure	Breakout 1, Topological Infrastructure Breakout 2, Spin Qubit Infrastructure
4:30 PM	*Breakout Summary Reports*	*Breakout Summary Reports*	*Breakout Summary Reports*
5:00 PM	*Adjourn*	*Adjourn*	*Adjourn*

A list of the breakout session panelists is provided below:

Day 1 – SC Qubit Infrastructure

- Andrew Cleland, University of Chicago (moderator)
- Machiel Blok, University of Rochester
- John Martinis, University of California, Santa Barbara
- Peter McMahon, Cornell University
- Anthony Megrant, Google
- Britton Plourde, Syracuse University
- Robert Schoelkopf, Yale University
- Irfan Siddiqi, University of California, Berkeley
- Christy Tyberg, International Business Machines

Day 1 – Trapped Ion Infrastructure

- David Goldhaber-Gordon, Stanford University (moderator)
- Joe Britton, University of Maryland
- John Chiaverini, MIT-Lincoln Laboratory

- Hartmut Häffner, University of California, Berkeley
- Patty Lee, Honeywell Quantum Solutions
- Christopher Monroe, Duke University
- Christian Ospelkaus, Hannover University
- Daniel Slichter, National Institute of Standards and Technology

Day 2 – Optics and Communication

- Mo Li, University of Washington (moderator)
- Hannes Bernien, University of Chicago
- Nathalie de Leon, Princeton University
- Dirk Englund, Massachusetts Institute of Technology
- David Fuchs, Cornell University
- Marko Loncar, Harvard University
- Arka Majumdar, University of Washington
- Galan Moody, University of California, Santa Barbara
- Shayan Mookherjea, University of California, San Diego

Day 3 – Topological Qubits

- Vlad Pribiag, University of Minnesota (moderator)
- Chris Palmstrøm, University of California, Santa Barbara
- Amir Yacoby, Harvard University
- Sergey Frolov, University of Pittsburgh
- Angela Kou, University of Illinois, Urbana Champaign
- Kin-Fai Mak, Cornell University
- Javad Shabani, New York University

Day 3 – Spin Qubits

- Steven Koester, University of Minnesota (moderator)
- Jason Petta, Princeton University
- Mark Eriksson, University of Wisconsin, Madison
- Mark Friesen, University of Wisconsin, Madison
- Hongwen Jiang, University of California, Los Angeles
- Ryan Jock, Sandia National Laboratory
- Douglas Natelson, Rice University
- John Nichol, University of Rochester

4. Attendees

In total, the workshop had 412 registered attendees. The attendees consisted of academic, industry and government researchers in the area at the intersection of quantum information sciences & engineering and nanofabrication. The breakdown of attendees was as follows:

- US Government (31)
- Industry (48)
- Non-profits (2)

- US university (325)
- Foreign university or laboratory (6)

5. Overview of presentations

5.1. Welcomes

Prof. Steven Koester (University of Minnesota) presented welcoming remarks on each day. On day 1, welcoming remarks were provided by Dr. Dawn Tilbury, NSF ENG Assistant Director, and Dr. Lawrence Goldberg, NSF ECCS Senior Advisor and NNCI Lead Program Officer. On day 2, brief remarks were also given by Dr. Alex Cronin, Deputy Director of the National Quantum Coordination Office (NQCO). Dr. Cronin provided an overview of the U.S. national strategy and coordination efforts for quantum information science, and introduced the Quantum Frontiers Report, which synthesizes community feedback based upon multiple QIS workshops and requests for information.

5.2. NNCI node presentations

On day 1, Prof. Oliver Brand (George Institute of Technology) provided an overview of the current NNCI network, with an additional overview on the quantum information science and engineering capabilities provided by the network. On days 2 and 3, prerecorded 5-minute presentations were given by 8 of the 16 NNCI nodes: nano@stanford led by Stanford University, Northwest Nanotechnology Infrastructure (NNI), led by the University of Washington, Research Triangle Nanotechnology Network (RTNN), led by North Carolina State University, Montana Nanotechnology Facility (MONT), led by Montana State University, Midwest Nano Infrastructure Corridor (MiNIC), led by the University of Minnesota, Cornell NanoScale Facility (CNF), led by Cornell University, The Center for Nanoscale Systems (CNS), led by Harvard University and Nebraska Nanoscale Facility (NNF), led by the University of Nebraska, Lincoln. In each of the node presentations, the speakers emphasized the quantum capabilities enabled by their nodes.

5.3. Center overviews

Overviews of three government-funded centers were provided, and the presentations are briefly reviewed here:

5.3.1. Center for Quantum networks

Prof. Saikat Guha (University of Arizona) provided an overview of the NSF-funded ERC: Center for Quantum Networks (CQN). The CQN has four thrusts: (1) Quantum network architecture, (2) Quantum sub-system technologies, (3) Quantum materials, devices, and fundamentals, and (4) Societal impacts of the quantum internet. The hardware technology aspects are primarily contained in Thrusts 2 and 3, with thrust 2 dealing with quantum repeater systems, error correction and fault tolerance and benchmarking subsystems, and thrust 3 focused on color center qubits, quantum materials and opto-electronic control.

Regarding infrastructure, Prof. Guha addressed some general thoughts on the shared infrastructural needs for quantum engineered systems, suggesting that a well-thought-out shared infrastructure is needed to overcome many of the challenges that currently hinder the development and adoption of quantum technologies. He suggested that broadly-accessible engineering capability across the spectrum of components and devices to software is needed, along with a robust workforce trained in these technologies. Prof. Guha suggested that collaboration at all levels is needed to integrate the different disciplines needed for complete quantum systems, and that coordination across centers, and government agencies is needed.

5.3.2. Quantum Foundry

Prof. Anya Jayich (University of California, Santa Barbara) provided an overview of the NSF-funded Quantum Foundry. The Quantum Foundry has three scientific thrusts: (1) Natively entangled materials, (2) Interfaced topological states, and (3) Coherent quantum interfaces. Dr. Jayich described the Quantum Foundry data science pipeline, which included development of growth and characterization of material and device properties, along with a goal to collect, curate, manage, catalog, integrate and analyze the various quantum-relevant materials. Dr. Jayich described many of the materials growth and integration capabilities being developed or are available within the foundry, including a vacuum suitcase network for UHV transfer of materials, various MBE epitaxial systems, a high-pressure laser float zone crystal growth tool, a diamond foundry tool suite, a van der Waals assembly system, and various low-temperature electrical and optical characterization systems.

5.3.3. Quantum Science Center

David Dean (Oak Ridge National Laboratory) provided an overview of the DOE-funded Quantum Science Center (QSC). The overarching goal of the QSC is to overcome key roadblocks in quantum state resilience, controllability, and scalability. Dr. Dean indicated that the main thrusts of the center are (1) achieving breakthroughs in materials science, aimed at accelerated quantum information processing, (2) development of quantum algorithms and software to predict new physical and chemical behaviors, and (3) studying new types of quantum sensors to explore phenomena that have previously been unmeasurable. Dr. Dean indicated that the QSC is well-positioned to overcome the roadblocks to achieving their goals by linking the capabilities of national labs and leading universities.

5.4. Topical presentations

Topical presentations on various qubit platforms, including superconducting qubits, trapped ions, color centers and optical communication, topological qubits and spin qubits, were provided at the workshop. It should be noted that these do not represent an all-inclusive list of the platforms for quantum engineering. Nevertheless, these presentations helped to provide an overview of the current status of research and development in these fields, and provided context for the infrastructure needs discussed in the breakout sessions. A brief overview of the topical presentations is provided below.

5.4.1. Superconducting qubits

5.4.1.1. Dr. William Oliver (MIT-Lincoln Laboratory)

Dr. Oliver provided an overview of superconducting qubits based upon Josephson junctions (JJs). Dr. Oliver provided a review of the basics of artificial atoms based upon Josephson junctions, where the key concept being that a Joseph junction acts as a non-linear inductor, thus creating an "anharmonic" LC oscillator when coupled with a capacitor (a so-called "transmon" qubit). Dr. Oliver provided an overview of the design parameters of transmons, including the small junction critical current, the junction self-capacitance, the shunt capacitance, the number of junctions in the array and the ratio of the large-to-small junction size. The small energy spacings for transmons on the order of 5 GHz, typically require dilution refrigerator (~20 mK) operation. Manipulation requires extensive microwave engineering and control. The improvement in $T_{1,2}$ coherence times was reviewed and over the last 20 years, with times increasing from a few nsec in 1999 to 100's of μsec in recent years. Such gains have resulted from improvements in materials, fabrication and design. Such an exponential trend forms a new type of "Moore's Law" for qubits. Dr. Oliver reviewed the noise mechanisms local to the qubit and showed how 3D-integration can improve isolation from many of these noise elements. In particular, he reviewed a full 3D integration platform developed at MIT-LL for quantum processors. This platform includes new innovation such as superconducting through-silicon vias (TSVs), which have advantages for readout/interconnect layer routing.

Dr. Oliver provided thoughts on a hybrid model where university lab can focus on rapid-development of new processes, while government labs such as MIT-LL can focus on high-yield, reproducible process development at larger scales. From an infrastructure point of view, Dr. Oliver indicated that infrastructure needs to focus on materials growth and analysis, fabrication engineering as well as test and measurement. He also acknowledged that a trade space exists and that investments in exploratory research and flexibility are often at odds with developing high-yield well-established processes, and this trade space must be managed appropriately.

5.4.1.2. Prof. David Schuster (University of Chicago)

Due to a last-minute scheduling conflict, Prof. Schuster was unable to give a presentation, but Prof. Schuster did participate in the superconducting qubit breakout session.

5.4.2. Trapped ions

5.4.2.1. Prof. Ken Brown (Duke University)

Prof. Brown provided an overview of trapped-ion quantum computers. There are two main functions of these systems: (1) Quantum gates, where laser pulses impinge upon multiple ions, and (2) Measurement devices, which consist of photon detection devices. Prof. Brown described the system components being assembled in his group to realize a trapped ion quantum computer, including cryostat, Raman lasers, ion imaging system and ion cooling and state selection system. He described the quadrupole electrode designs used for ion trapping, and surface treatments used to mitigate noise and heating effects. Finally, Prof. Brown described monolithic circuit integration approaches for trapped ion quantum computers, and provided a materials “wish list” for improving the performance of various components. These are as follows: (1) Metallic conductors used for ion trap electrodes require low RF loss, but electric-field noise from the surface remains a concern. (2) Transparent conductors are needed for dielectric shielding require high conductivity and optical transparency, but suffer from surface-induced electric-field noise. (3) Integrated optical modulators require low optical loss and large electro-optic coefficients, but these figures of merit are difficult given the large photon energies compared to conventional optoelectronics. (4) Single-photon detectors are needed for qubit readout, but can have backaction on ions and often are not CMOS compatible. (5) Other electronic components and interlayer dielectrics have noise, power dissipation and B-field noise issues.

5.4.2.2. Dr. Susan Clark (Sandia National Laboratory)

Dr. Susan Clark provided an overview of the Quantum Scientific Open User Testbed (QSCOUT) and Trap Foundry programs at Sandia. While the QSCOUT program seeks to provide a quantum testbed up to 32 qubits for users, the Trap Foundry seeks to design, build and distribute surface ion traps to groups around the world for quantum information research. Dr. Clark went on to describe the different trapped-ion architectures, and ways to address and detect the individual ions. After describing the JAQAL assembly language and initial user results, she discussed future upgrades to the Sandia qubit platform, including methods to expand beyond 32 qubits. These include waveguides and detectors integrated in the trap for individual addressing and detecting, new trap architectures with shuttling, and multi-species sympathetic cooling. Dr. Clark also discussed some of the advantages of the Sandia trap design, and how users can access these devices.

5.4.3. Color centers and quantum optical communication

5.4.3.1. Prof. Jelena Vuckovic (Stanford University)

Prof. Vuckovic described color centers for use in quantum repeaters and communication networks. Such systems require homogeneous, long lived qubits with optical interfaces, and efficient optical interconnects. She compared color center qubits with superconducting qubits the following way. Superconducting qubits in a microwave cavity have the advantage of being compatible with large, traditional microfabrication environments, but have no direct optical interface and require dilution refrigerator temperatures. Color center qubits act as artificial atoms in an optical cavity, and while they suffer from more difficult fabrication challenges, have the advantage of using semiconductors, have potential for higher-temperature operation, possess a natural optical interface, and can perform more gate operations within the qubit coherence time. She then described the different color centers in diamond and SiC based upon different impurity-vacancy complexes. She also described some of the process challenges and ways of dealing with inhomogeneities and tunability in diamond and SiC quantum optical systems. Dr. Vuckovic also explained the different process approaches for quantum photonics, for instance thin-film vs. 3D “carving”. She further provided a detailed description of how to realize integrated photonic circuits based upon SiC, and reviewed the state-of-the-art status in quantum networking.

Finally, Dr. Vuckovic provided some thoughts on the main challenges to scaling up semiconductor quantum systems. These are as follows. The main fabrication challenges for color-center-based quantum computing are (1) inhomogeneities in qubits placed in photonic structures (spatial, spectral), (2) designing and fabricating highly-efficient and high-density photonics, and (3) fabrication and integration using hard materials such as diamond and SiC. In terms of the long-term fabrication challenges that the NSF-funded research community could focus on, Prof. Vuckovic identified (1) reducing inhomogeneities (regular arrays with high yield of high-quality qubits, minimal inhomogeneous broadening), (2) efficient photonics using SiC, diamond, etc., and (3) developing reconfigurable heterogeneous photonics and hybrid circuits. Finally, in terms of fabrication infrastructure (e.g. equipment / processes) needed to support long-term research, she listed (1) irradiation/implantation, (2) growth of high purity and isotopically purified materials, (3) production of high purity thin films of diamond and SiC, (4) heterogeneous materials processing and integration, and (5) foundries for novel materials.

5.4.3.2. Prof. Kai-Mei Fu (University of Washington)

In this talk, Prof. Fu provided an overview of color centers for quantum computing and communication, discussed the main fabrication challenges for color-center-based quantum computing, and addressed the long-term fabrication challenges on which the NSF-funded research community could focus. Prof. Fu also discussed the fabrication infrastructure (e.g. equipment / processes) that are needed to support long-term research in this field.

Prof. Fu first discussed the advantages of defect-based color centers, which include long spin coherence times, stable and efficient spin-optical coupling, and generation of identical photons. A typical design cycle includes: (1) creating and characterizing defects, (2) device design, (3) photonics device fabrication, and (4) device testing, and that shared facilities could help to accelerate bottlenecks at all levels. For defect creation and characterization, while commercial diamond is available, particular challenges include etching the diamond layers, ion implantation of nitrogen atoms and high-temperature annealing. For instance, NV-centers created via ion implantation have energy level variation that is still orders of magnitude too high for quantum applications. For device design, simulation is expensive and can be a significant portion of the total fabrication budget. The photonics integration is a multi-step process requiring: layer transfer and adhesion, optical and electron-beam lithography, RIE etching, metal deposition, HF-vapor and XeF_2 etching. Both equipment and process knowledge are important to realize a successful integration flow. Prof. Fu indicated that access to additional materials for photonics integration would be particularly helpful. These include access to nonlinear / waveguiding materials (e.g. GaP and AlN), piezoelectric materials (e.g. ZnO) and superconducting films (e.g. NbN). Finally, device testing remains a challenge, and proxies to full device testing, such as passive testing using microscopic or surface analytic methods, are needed.

5.4.3.3. Prof. Dirk Englund (Massachusetts Institute of Technology)

Prof. Englund provided a motivation for quantum networks, but indicated that the limitation is the quantum repeater, which has not yet been demonstrated, and has the challenge of scalability once it is realized. He then described the evolution of diamond photonic processing, which has improved greatly in the last 10 years, going from single "hero" devices to thousands of working devices on a single chip. In terms of color centers, Prof. Englund said that research needs to continue along two fronts: the discovery of new and better color centers, and scaling up of the best technologies in hand. He also discussed the precision placement of color center dopants via ion implantation, a process that needs to be made more broadly available to the community. Prof. Englund describe his research group's approach to scaling-up quantum network systems which are based upon commercially-available AlN photonic elements integrated with pick-and-place diamond photonics. This approach allows extremely-high yield to be achieved. Though the intrinsic color center properties are not perfect, strain engineering can be used to tune and align the emission wavelengths. Therefore, the ability to scale individually controllable spin-qubit-clusters and connect several by photons has been achieved. He also showed that these devices allowed the demonstration of quantum advantage in memory-based quantum communication. Prof. Englund further described details of various architectures for quantum networks, including quantum routers, as well as the MITRE-MIT-Sandia NL Quantum moonshoot project, which has the goal to develop a scalable quantum photonic integrated circuit platform.

Regarding infrastructure needs, Prof. Englund described the main challenges for color center research as being: (1) an accessible, visible-spectrum quantum integrated circuit platform integrated with analog electronics, and (2) a foundry service for diamond. For the former point, these exist in specialized fabs, but not generally available. The latter would enable an eco-system for a data-driven, closed-loop materials and fabrication development focused on diamond.

5.4.3.4. Prof. Marko Loncar (Harvard University)

Prof. Loncar motivated his talk by discussing the interconnect bottleneck in quantum networks and the need for quantum repeaters and transducers. He initially introduced color centers for quantum memories, and the advantages and disadvantages of the different types. Prof. Loncar described the state-of-the-art cavity-coupled SiV color center technology, which has been used to demonstrate single-photon switches, memory-enhanced quantum communication, and other milestones. He described how strain can be used to tune the emission properties, which allows for strain-tuning-induced photon entanglement, and opens up the possibility of using mechanical quantum gates.

Prof. Loncar also described the optical component requirements for quantum photonic networks, including both visible and telecom compatibility, low loss and high-speed operation, and how $LiNbO_3$ (LN) can meet these requirements, whereas Si and Si_3N_4 cannot. LN has high index, large non-linearity and a wide transparency window, but is hard to process and generally only available in bulk. Prof. Loncar showed their progress on thin-film integrated LN photonic elements, and how these elements can be used for quantum photonics. He particularly described "photonic molecules" based upon coupled ring resonators and how coherent control of single photons can be achieved using microwave fields. Finally, Prof. Loncar emphasized the utility of LN for a wide range of quantum photonic applications.

5.4.4. Topological qubits

Two presentations were provided on topological qubits by Prof. Chris Palmstrøm (University of California, Santa Barbara), and Prof. Amir Yacoby (Harvard University)

5.4.4.1. Prof. Chris Palmstrøm (University of California, Santa Barbara)

Prof. Palmstrøm provided a general background on Majorana Zero Modes (MZMs), which are non-abelian anyons - which is a type of quasiparticle that occurs only in reduced-dimensional systems. Non-abelian anyons have the property that they can "remember" if they were moved clockwise or anti-clockwise around each other, a concept called braiding. This braiding property provides MZMs with protection from environmental disturbances, making them highly interesting as the basis for error-free quantum computing. Prof. Palmstrøm highlighted the primary "recipe" for creating MZMs, which is to create a nanowire in a material with large spin-orbit interaction, which is coupled to an s-wave superconductor and placed in a magnetic field. Such structures have been realized, but have not conclusively shown evidence of MZMs, and Prof. Palmstrøm highlighted the materials challenges in realizing sufficiently pure structures needed to observe MZMs, and also the challenges to realizing the higher levels of integration needed for realistic quantum systems. He also pointed out that trivial zero-bias conductivity features can mimic true MZM behavior, highlighting the need for improved materials and experimental methodology. Materials improvement progress reviewed by Prof. Palmstrøm included selective area growth, which can help to build arbitrary network of coupled nanowires, techniques to further improve the mobility in InAs quantum wells and *in-situ* deposition of the semiconducting/superconducting materials. He also noted that a wide range of both semiconducting and superconducting materials need to be explored, highlighting the early stage of research in this area.

In terms of the main materials challenges for topological-based quantum computing, Prof. Palmstrøm highlighted: (1) controlling disorder and defects in the semiconductor and superconductor, (2) surface and interface passivation, (3) identifying the optimal material system, and (4) differentiating MZMs from Andreev bound states and observing braiding/qubit operation. Prof. Palmstrøm also suggested that controlling material surfaces and interfaces via *in-situ*/inert environment processing is one of the long-term materials challenges that NSF-funding could help to address. He also suggested that UHV fabrication combined with characterization and testing at mK temperatures in high magnetic fields is a significant challenges that requires long-term research investment.

5.4.4.2. Prof. Amir Yacoby (Harvard University)

Prof. Yacoby's presentation began with a reminder of the goal of topological quantum computing: to achieve decoherence-free encoding and manipulation of quantum information. To achieve this goal, he highlighted the key engineering challenges to realizing topological qubits, which are to:

(1) develop new materials platforms for topological superconductivity, and (2) to control the interface between superconductivity and quantum phases of matter. Prof. Yacoby's talk focused on such new platforms, with an emphasis on 2D systems. He reviewed the different 2D topological superconducting platforms and focused particular attention on Josephson junctions with strong SO coupling, and showed theoretical and experimental evidence that such structures could support a topological superconducting phase that is robust to disorder. Ways to couple superconductivity to integer and fractional quantum Hall states as a possible means to achieve more universal topological quantum computing were also reviewed. Finally, Prof. Yacoby reviewed the different material platforms for different types of planar topological qubits, suggesting that additional materials platforms need to be studied an investigated.

5.4.5. Spin qubits

5.4.5.1. Prof. Mark Eriksson (University of Wisconsin, Madison)

Prof. Eriksson began by emphasizing that academia, industry, and national labs all have a critical roles to play in ensuring a viable fabrication infrastructure for spin qubits. Prof. Eriksson provided an overview of gate-defined quantum dot (QD) fabrication and the various types of qubits that can be implement using Si/SiGe quantum wells. Prof. Eriksson next explained one of the key challenges for spin-based qubits in Si, which is how to design materials with enhanced valley splitting. He showed that both intra-zone and inter-zone couplings can be used to generate valley splittings, and emphasized a specific techniques to control the coupling between the first and second Brillouin zones. This technique, whereby the Ge concentration in the quantum well is modulated at the wavevector that couples the inter-zone valleys, was shown to produce valley spacings as large as 0.2 meV. Prof. Eriksson also emphasized the need for fabrication advances to create high-fidelity gate control signals. These include the integration of low-impedance microstrips to reduce photon loss while maintaining wide bandwidth for driving gates. Such microstrips can also reduce cross-talk between gate leads. Finally, Prof. Eriksson described the importance of materials integration. He particularly emphasized the problem of charge noise as being a pervasive problem in QD qubits. A particular problem in Si/SiGe quantum wells is the surface oxide, which must simultaneously use low-temperature processing to preserve the Si/SiGe interface, have low fixed charge density, have high breakdown field, and have low charge noise figure of merit. He suggested that low-temperature-grown SiO_2 could provide a better solution than deposited Al_2O_3.

5.4.5.2. Prof. Jason Petta (Princeton University)

Prof. Petta provided an overview of QD based qubits. He first described the DiVincenzo criteria for qubits including efficient initialization, readout, a universal set of gate operations, long coherence times and scalability, as well as the Loss & DiVincenzo proposal for QD-based qubits. He then provided an overview of the first demonstration of spin qubits in GaAs QDs. These are limited by the nuclear spin dephasing problem, which then led to a "pivot" toward Si QDs. Si QDs have demonstrated extremely long spin lifetimes, which has been further improved using isotopic enrichment. Si QDs also have extreme scalability. However, valley splitting and large effective mass are two difficulties in Si QD qubits. Prof. Petta then showed his group's progress in this area, by using high-mobility Si quantum wells on relaxed SiGe buffer layers based upon accumulation-mode, overlapped gate stacks. He showed various generations of qubits, from single qubits to multi-dot arrays, as well as functional demonstrations, including a resonant CNOT gate, and a 9-dot charge shuttle. Prof. Petta also showed spin qubits could be coupled to a superconducting cavity to allow long-distance spin-spin coupling. He further used this concept to demonstrate a spin-photon strong coupling device architecture. For more advanced fabrication, Prof. Petta described plans to move to 3D integration. This involves a flip-chip fabrication scheme to combine the Si/SiGe and superconducting components.

Prof. Petta then described the fabrication challenges for Si/SiGe QD qubits. These involve multiple aligned electron-beam lithography steps, and a range of other processing steps. He emphasized the need for good uptime and tool maintenance, as well as strong staff support, and the hiring of process staff who can be involved with novel process development. He also noted that processing facilities with a large number of users need to ensure the equipment performs well for the small number of heavy users. He noted that his group's process requirements for QD spin qubits include ~10-nm-resolution electron-beam lithography, with similar overlay accuracy, direct-write photolithography and Al deposition and oxidation. In the future, he expected that greater emphasis would be placed on semiconducting / superconducting hybrid integration using flip-chip bonding, more extensive wire-bonding, the use of subtractive processing instead of lift-off, and planarized processing for improved multi-layer structures.

5.5. Breakout sessions

The primary conclusions arising from each of the breakout session are summarized below. These include comments from the panelists, as well as those attendees who participated in the discussions.

5.5.1. Superconducting qubits

The conclusions from the superconducting qubit breakout session are summarized below:

- Infrastructure support does not necessarily just mean tools. It could also consist of unit processes, and validated process flows. When considering infrastructure investments, all three of these must be considered. While general research access to validated process flows may not be realizable, sharing making available unit processes for steps such as angled evaporations is an achievable goal.
- The central NNCI hub primarily advertises tool availability, but there is a greater need to advertise and support unit processes and validated process flows. Such process-level support could be especially important for new faculty or sites without this capability in house. Cross-testing of standard devices between different labs could be a good way to validate such shared process recipes.
- Questions arose in the panel session about how to share information about processing best practices. Two main suggestions were provided. The first was to hold a workshop for staff engineers so that such information could be shared among staff at the different NNCI sites. The second was to share process information from government labs with more mature processes, such as MIT-LL. However, the latter suggestion might require higher-level government approval.
- The panel pointed out the dichotomy for researchers in that there is a need for research access to a stable and reliable qubit process, but at the same time, ways to explore process variations is needed to identify improved approaches.
- Having shared facilities for characterizing materials, processes, and devices is a very important part of shared infrastructure needs in this area.
- Packaging tooling for superconducting qubits is complex and expensive, and requires dedicated staff for operation. How to provide access to state-of-the-art packaging remains an open question, although for materials and device-based development this is not a critical a need.

5.5.2. Trapped ions

The conclusions from the trapped ion breakout session are summarized below:

- Research on ion-trap quantum computing is difficult at the university level, due to the complexity of the infrastructure needed to realize the various system components. There have been examples of full ion trap quantum computers being built at universities, but it took a lot of investment and effort to realize.
- A more modular approach, for instance where a novel ion trap could be made and the rest is acquired from external sources, would help to enable academic research participation in this field.
- Developing testbeds for something less than full quantum computer, to test relevant phenomenology and components that could eventually be transferred to government or industry labs, would be desirable.
- Various available testbeds exist for trapped ions exist, such as Sandia and LBNL, which do allow outside users hands-on access to a working ion trap quantum computer, but under-the-hood manipulation with hardware platform is limited.
- Could some kind of foundry to go beyond standard designs be developed? This would require dedicated staff plugged into the field, to incorporate new developments.
- ARTIQ and associated open hardware projects are valuable. It would be helpful to advertise this capability to potential researchers.
- There is a need for new research in this field, particular to enable higher-level (e.g. > 32 qubit) architectures. These will require integrated waveguides and detectors, and new ways to allow ion shuttling. This could be an opportunity for academic researchers.
- Additional technical challenges include challenges optical coupling to fibers, decoupling mechanical vibrations, identifying electrical noise sources, generating appropriate UV laser light, and short-wavelength waveguide technology.
- The panel recommended organizing a follow-up workshop that brings together tool vendors with the nano and quantum communities, specifically those who are not building systems at IARPA/DARPA scale to see where they can outsource custom parts to industry.

5.5.3. Color centers and quantum optical communication

The conclusions from the color center and quantum optical communication breakout session are summarized below:

- Material supply remains a critical problem in terms of how heterogenous materials and processes can be made available to the broader research community.
- One suggestion to overcome the material supply problem was to develop a government subsidy model that could help to create the market for high-quality material.
- More capabilities around the US to make RF and optical packages for qubits are also needed.
- Programs to address some of the “grand challenges” in quantum photonics are needed. Examples could be a program that provides a device or system demonstrator involving 3D photonics.
- Additional investment in visible spectrum photonics in a variety of materials is also needed.
- Regarding NNCI resources, the following recommendations were made:
  - Tool and process sharing remains a critical role for NNCI to play.

  - NNCI could also play a role in facilitating "tech transfer" where know-how, materials, and fabrication processes can be proliferated through the academic community from particular research groups.
  - Investment in NNCI graduate student fellowships could be a possible mechanism for students to transfer their knowledge to process staff.
  - More research facilities for quantum photonic packaging could be part of future NNCI investment.
  - Infrastructure for bulk characterization tools that cannot be obtained in the US (e.g. high-resolution SIMS, miscut characterization) needs to be supported.
  - Major research infrastructure (MRI) grants, coordinated with the NNCI facilities focused on quantum infrastructure could be a way to provided needed infrastructure.
  - Some thought should be given to how NNCI sites can include some type of specialized service for quantum materials or processes, perhaps through a supplemental funding mechanism. At minimum, NNCI could be involved in coordinating such services through a portal.

5.5.4. Topological qubits

The conclusions from the topological qubit breakout session are summarized below:

- There was broad agreement that a need exists to increase the materials base for topological devices. This could include materials and interface engineering for both 1D and 2D-based platforms. This could include broadening the notion of a traditional nanofab, and that the traditional separation between growth and fabrication need to be blurred to allow future progress.
- As an example of the materials needs, the ability to stack layered materials is critical to exploring many 2D-material-based topological platforms. While some groups have stacking capabilities, few have them integrated into a larger fabrication environment. Therefore, the panel recommended additional infrastructure for automated stacking and integration with nanofabrication. Specification recommendations include:
  - Automating / standardizing fabrication techniques
  - Joint efforts between academia and industry to develop layer stacking tools
  - Machine-learning-based identification / screening of exfoliated materials
  - Moving away from exfoliation to using large-area-grown materials, including developing techniques to directly grow stacked 2D materials
- A need also exists to better protect surfaces during processes that require hybrid materials (e.g. semiconducting / superconducting interfaces).
- Support for characterization infrastructure was deemed to be particularly important. Suggestions included:
  - Closer coupling between fabrication and characterization in a close loop fashion.
  - Further discussion is needed as to the extent that different types of characterization closely coupled to the fab that are needed may needed (e.g. only transport measurements, or including AFM, SEM, etc?)
- Regarding NNCI resources, the following recommendations were made:
  - The notion of NNCI could be broadened to incorporate materials growth. Much more materials infrastructure is needed.

    - For topological devices, given the exploratory nature of the field, cleanroom facilities need to be more versatile, rather than focused on a small set of processes.
    - Support for process engineers is important to preserve and archive process knowledge.
    - Improvements in how non-NNCI sites can access key capabilities is needed.
    - Support for more basic equipment acquisitions for key characterization steps is needed.

5.5.5. Spin qubits

The conclusions from the spin qubit breakout session are summarized below:

- Spin qubits based upon QDs require dedicated, high-quality electron-beam or deep ultra-violet optical lithography. These devices also require multiple lithographic levels with precision alignment.
- Spin qubits also need other precision processes, including dielectric deposition, cleaning, and dry etching.
- Access to high-quality material is critically important for QD spin qubits. Currently, only a few collaborative suppliers exist. Progress requires that reliable access can be achieved, without imposition of restrictions for work with the academic community.
- One panelist suggested a hybrid fabrication model where ¾ of the fabrication could be performed by a dedicated supplier, and then the fabrication could be completed in academia. Such a model could lower the barrier to entry for new faculty, and allow small-team or even single-investigator proposals. This “partial foundry” model could include supplying “starter chips” to academia, which could include test structures that validate material quality.
- Research requires knowledge sharing to develop feedback between nanofabrication and device performance. Therefore, cryogenic testing is an important part of the overall infrastructure.
- Regarding NNCI resources, the following recommendations were made:
    - One panelist suggested that certain NNCI sites could be focused on a specific technology. This capability could help to ensure that processes with a high-level of maturity could be maintained within the NNCI.
    - More ways to obtain access to needed materials are needed.
    - Improved methods to enable information sharing on key dedicated processes and tool capabilities are needed. For instance, resources could be made available to train students to make qubits. This could take the form of an “NNCI fellow” who could be paired with a physics student to learn key processes that could then be propagated more efficiently through the network.
    - In general, more overall resources (e.g. funding) are needed. Having NSF coordinate with other government agencies could also be helpful.

6. Main Conclusions and Recommendations

Several unifying conclusions and recommendations were determined from the workshop.

1) Several NNCI nodes have already made significant investments to provide infrastructure for quantum engineering and science research, and have made significant contributions to

state-of-the-art demonstrations in quantum engineering research. This infrastructure needs to be maintained and utilized to its fullest extent.

2) It is recognized that quantum infrastructure needs are complicated by the vastly different nature of quantum computing and communication platforms. Some platforms are more mature, such as superconducting and trapped ion qubits, while others, such as topological qubits, are much more at the basic research level. Therefore, quantum processing infrastructure needs to support technologies that require higher-levels of integration, yet have the flexibility to work with emerging platforms.

3) Several panelists and speakers indicated that a mechanism to provide access to mature technology platforms is needed. This could take several forms, including a “three-quarters” process where a chip is fabricated most of the way through, but then provided to researchers to complete, a foundry model where a company or national lab provides technology access using a multi-project wafer process, or even a model with a specific NNCI node specializes in a particular technology which can then be accessed by the broader community. While such mechanisms were discussed and are desirable in theory, practical barriers to these mechanisms would have to be overcome.

4) A greater emphasis on materials research in a way that helps to improve the supply / availability of key materials was also highlighted as an urgent need. Materials include Si/SiGe heterostructures, materials for color centers such as diamond and SiC, and assembled 2D material stacks. Some applications would benefit from isotopically-pure materials (as added layers) as well.

5) It was pointed out by several speakers that mechanism for developing and maintaining process knowledge within the NNCI staff is also needed. Each qubit technology tends to use a set of more-or-less common materials and basic processes, but designs that transform the basic elements into a functional unit are usually bespoke and require local capabilities and expertise. This results in a need for a national or regional knowledge base supported by shared capabilities such as growth or characterization, but complemented by support for local or regional capabilities for making functional assemblies. One suggestion to achieve this goal was to create and fund an NNCI “fellows” program. These fellows would be graduate students or postdocs tasked with learning and transferring process knowledge to NNCI staff and the associated research community. Such a program could be feasible if it could be integrated into those students’ or postdocs’ academic programs. Quantum infrastructure might also benefit from a common website or place where information could be collected. NNCI.net has links and search capabilities, but needs consolidation and expansion.

6) Characterization needs (both at the device and materials level) cannot be ignored. Dilution refrigerator access is limited to individual faculty laboratories. Faster turnaround between fab and testing is critical across multiple platforms in order to speed research progress.