WORKSHOP ON QUANTUM ENGINEERING INFRASTRUCTURE II FINAL REPORT

EXECUTIVE SUMMARY

The Workshop on Quantum Engineering Infrastructure II (WQEI2) was held on March 3, 2024, in Minneapolis, MN, on the campus of the University of Minnesota. The workshop was sponsored by the National Science Foundation (NSF) and had three main goals:

(1) To assess the outcomes from the 2021 WQEI and evaluate progress toward recommendations from that workshop.

(2) To understand how new developments in quantum computing have altered the needs and best practices for quantum fabrication infrastructure since 2021.

(3) To provide a vision for the future of quantum fabrication infrastructure in the United States so that shared national resources meet the needs of quantum engineered systems.

The workshop was a hybrid event with 115 registered attendees in total, with most from US universities, but with other attendees from government, industry, national laboratories, and foreign universities. A total of 54 people attended in person. The main topical areas covered were superconducting qubits, spin qubits, color centers, and emerging quantum platforms. The format consisted of a combination of overview talks and panel sessions.

Several conclusions and recommendations were formulated, with the most important of these summarized below. A comprehensive list of recommendations is provided in the full report.

1) Research on qubits is still in its early stages, and so fundamental research remains critical, even on mature qubit platforms. NNCI facilities provide important infrastructure to support this research. Fundamental understanding of materials and interfaces remains a paramount concern.
2) The fabrication requirements to advance the various qubit platforms are often very different, with more mature technologies requiring more CMOS-like processing, while emerging platforms require highly customized equipment and infrastructure. User facilities supporting quantum research need to be able to bridge between these requirements.
3) Hubs and partnerships between academia, US government labs and industry, are critical for advancing quantum research, with academia focusing on education and emerging concepts, government labs focusing on process refinement and prototyping, and industry executing scale-up.
4) Focused funding programs for quantum-specific equipment would be helpful, and coordination of the MRI program with national infrastructure programs such as NNCI could help to ensure equipment resources are used to advance research in the most efficient and effective way possible.
5) Characterization equipment, such as in-line optical characterization and cryo-probers for fast process turn-around are an important part of the infrastructure environment for qubit research.
6) There is an across-the-board need for trained technical staff at university fabrication and characterization facilities, not just for maintenance, but to accelerate the field. Staff need to have the ability to attend conferences and collaborate on tool process development. Importantly, staff time must be allocated so they can sufficient bandwidth for these activities.

1. Workshop Date and Locations

The workshop was held on March 3, 2024, in Minneapolis, MN, on the campus of the University of Minnesota. Most attendees were in-person, but a hybrid option was also provided.

2. Organizing Committee

The organizing committee was as follows:

- Steven Koester (University of Minnesota) (Conference, Session chair)
- Vlad Pribiag (University of Minnesota) (Session chair, Breakout moderator)
- Andrew Cleland (University of Chicago) (Session chair, Breakout moderator)
- Ruoyu (Roy) Li (IMEC)
- Karl Böhringer (University of Washington)
- Thomas Schäpers (Forschungszentrum Jülich)
- Robert Westervelt (Harvard University)
- David Gottfried (Georgia Institute of Technology)
- Martin Mourigal (Georgia Institute of Technology)
- Juliet Gopinath (University of Colorado – Boulder)

3. Workshop Program and Format

The speakers and panelists were by invitation only. The invited speakers were chosen by topical area, so that as many relevant aspects of solid-state quantum information science and engineering can be covered as possible. However, some important areas were omitted due to time considerations, such as cold atom and trapped ion qubits, and quantum sensing. The topical areas covered were superconducting and spin qubits, color centers, and emerging platforms. At the start of each session, a speaker provided an overview of the field and then was followed by a panel session where curated questions were asked of the panelists. Organizing committee members acted as session chairs and breakout moderators. The full program agenda is shown in Figure 1.

Time (CST)	Agenda
09:00 AM	Arrival, registration, and continental breakfast
10:00 AM	Welcome
10:10 AM	**Superconducting qubits** – Overview presentation: William Oliver
10:30 AM	Panel 1 – superconducting qubits: William Oliver, Kyle Serniak, Santino Carnevale, Robert Visser
11:00 AM	Panel 1 – Q & A
11:20 AM	*Break*
11:35 AM	**Spin qubits** – Overview presentation: Mark Eriksson
11:55 AM	Panel 2 – spin qubits: Mark Eriksson, Dominik Zumbuehl, Arne Laucht, Thaddeus Ladd
12:25 AM	Panel 2 – Q & A
12:45 PM	*Lunch*
01:45 PM	**Color centers and optics** – Overview presentation: Kai-Mei Fu
02:05 PM	Panel 3 – color centers and optics: Neil Sinclair, Greg Fuchs, Kristiaan De Greve, Gary Wolfowicz
02:35 PM	Panel 3 – Q & A
02:55 PM	*Break*
03:10 PM	**Emerging platforms** – Overview presentation: Sergey Frolov
03:30 PM	Panel 4 – Emerging platforms: Sergey Frolov, Chris Palmstrøm, Christoph Stampfer, Javad Shabani
04:00 PM	Panel 4 – Q & A
04:15 PM	Wrap up: discussion of outcomes
04:45 PM	*Adjourn*

Figure 1. WQEI2 final agenda and timeline.

A full list of the speakers and panelists is provided below:

Superconducting Qubits

- *Andrew Cleland, University of Chicago (session chair and moderator)*
- William Oliver, MIT (overview speaker and panelist)
- Kyle Serniak, MIT – Lincoln Laboratories (panelist)
- Santino Carnevale, IBM Research (panelist)
- Robert Visser, Applied Materials (panelist)

Spin Qubits

- *Steven Koester, University of Minnesota (session chair and moderator)*
- Mark Eriksson, University of Wisconsin – Madison (overview speaker and panelist)
- Dominik Zumbühl, University of Basel (panelist)
- Arne Laucht, University of New South Wales and Diraq (panelist)
- Thaddeus Ladd, HRL Laboratories (panelist)

Color Centers and Optics

- *Steven Koester, University of Minnesota (session chair and moderator)*
- Kai Mei Fu, University of Washington (overview speaker)
- David Fuchs, Cornell University (panelist)
- Neil Sinclair, Harvard University (panelist)
- Gary Wolfowicz, Photonic (panelist)
- Kristiaan De Greve, IMEC (panelist),

Emerging Platforms

- *Vlad Pribiag, University of Minnesota (session chair and moderator)*
- Sergey Frolov, University of Pittsburgh (overview speaker and panelist)
- Chris Palmstrøm, University of California, Santa Barbara (panelist)
- Javad Shabani, New York University (panelist)
- Christoph Stampfer, RWTH Aachen University (panelist)

4. Attendees

In total, the workshop had 115 registered attendees. Attendees were from academic, industry and government labs and included experts in both quantum information sciences and nanofabrication. In total, 54 people attended in person. The breakdown of registered attendees is as follows:

- US government (11)
- Industry (18)
- US university (80)
- Foreign university or laboratory (6)

Attendance was free and the conference attendance was solicited via e-mail and social media. One of the LinkedIn announcements is provided in Figure 2 below.

Figure 2. Announcement for workshop posted on LinkedIn.

5. Overview of Presentations

5.1. Welcome

Due to the short single-day schedule, the introductory remarks were kept relatively brief. Dr. Steven Koester provided an introduction and described the goals of the workshop, which were to (1) assess the outcomes of the previous workshop in 2021, (2) understand new developments in quantum computing that affect infrastructure, and (3) provide recommendations for future investments in quantum fabrication infrastructure. Richard Nash from NSF also provided a brief introduction noting that the workshop will help to guide the strategy for future infrastructure programs that support quantum engineering.

5.2. Session 1: Superconducting Qubits (Andrew Cleland, Chair)

5.2.1. Overview presentation

The first session overview presentation was given by Prof. William Oliver (MIT) (Figure 3). Dr. Oliver provided an overview of the superconducting qubit field, with a focus on Josephson Junction (JJ) qubits based upon the anharmonic LC oscillator that is formed when the JJ acts as a nonlinear inductor element.

Figure 3. Overview speaker slide for session 1: Superconducting Qubits.

Dr. Oliver noted that the number of operations before an error is the key metric for all qubits and that superconducting qubits have progressed tremendously in recent years, with fidelity on the order of

99.99% now possible. However, he said that the need for quantum error correction implies that **orders of magnitude improvements** are still needed, with on the order of 1 in 10^9-10^{12} error rate ultimately needed.

Therefore, he strongly emphasized the need better and better qubits, and that achieving this goal remains very challenging. Dr. Oliver indicated that he sees improvements needing to come from 3 main areas: materials, fabrication, and design. Of these, he said the emphasis needs to be on materials and fabrication, which still need significant improvement. He noted that dielectric loss is not the only loss mechanism that needs to be tackled, and that quasiparticle tunneling through junctions, charge fluctuations, magnetic field fluctuations, and even modes that relate to the environment of the qubit are important. Dr. Oliver emphasized the difficulty in optimization to deal with all of these issues simultaneously because they are often interdependent and solving one problem can create another. He said that surface and material science is becoming increasingly important, and there is also a need to understand losses in more complex structures, such as three-dimensional (3D) integrated structures.

Dr. Oliver's main takeaways were as follows:

(1) **Superconducting qubits are transitioning and need improved infrastructure** that is related to materials, growth, analysis, fabrication, cryogenics, and control and continue to optimize this virtuous cycle.

(2) **The community needs to do more through hubs and partnerships** between academia, US government labs and industry. Academia can focus on education on new concepts. Government labs can do refinement, prototyping, and foundry services. (He emphasized that a foundry is a place that makes "your" devices. A user facility is not a foundry. User facilities are where people make devices for themselves.) Finally, industry is where we execute scaling and can develop tools which are necessary for design.

(3) **Cost is a challenge.** The community needs foundry services from key facilities (e.g. MIT-LL for superconducting qubits, HRL and Intel for semiconducting qubits), in order to address the cost challenges, while still ensuring progress.

5.2.2. Panel session #1

Panel #1 was on superconducting qubits and consisted of Santino Carnevale (IBM), William Oliver (MIT), Kyle Serniak (MIT-LL) and Robert Visser (AMAT). (Figure 4). Each panelist was asked a unique question aimed at their expertise. In this case, the panelists represented different types of research institutions such as academia (Oliver), government labs (Serniak), industry (Carnevale), and commercial tool manufacturers (Visser).

Figure 4. Contributors for panel session 1: superconducting qubits.

The questions were mainly aimed at understanding the main factors that would allow the further upscaling of superconducting qubit technology, and the associated fabrication challenges. The questions also touched on the challenges associated with how tool manufacturers can support research and development in superconducting qubits.

The primary conclusions from panel #1 (Superconducting Qubits) were as follows:

(1) **Despite significant improvement in superconducting quantum computing since the last workshop, the field is still in its early days**. While qubit phase coherence times have continued to steadily improve, and two-qubit entangling gate fidelity has also improved, the required coherence times are a long way from being sufficient for error-free computing. Nevertheless, there was a general feeling of optimism that process can be made, and that no fundamental roadblocks to achieving further advancements.

(2) The panel re-iterated the **need for fundamental improvements in materials and fabrication**, which are critical for superconducting qubits, as well as the specific qubit architectures, including transmon-style qubits and other emerging platforms such as fluxonium qubits. The panel also emphasized the need for further development in characterization, especially in measuring, understanding, and eliminated two-level systems (TLS).

(3) While significant improvements in individual qubits are needed, **attempts to improve coherence times must be made in a way that is scalable.** For instance, the panel felt that replacing the Dolan Bridge mode of JJ fabrication was needed, but in a way that was scalable to larger qubit numbers, for instance using subtractive processing and modular process flows. Such an approach would allow process development at each step, as opposed to all-at-once processing. If CMOS-like process approaches could be used to achieved these goals, they should be utilized. The panel did note that dedicated tools for the most critical process steps may be needed, including depositing, and etching of the superconducting circuits, to ensure process controllability.

(4) The panel felt that **it is still be too early for quantum-specific tool development at the commercial level.** Instead, existing toolsets should be used, since there is not a mature technology or a sustainable quantum business at present. Most importantly, there are still too many approaches being considered. However, some customization for quantum could take place in user facilities and government labs, and dedicated quantum tools may eventually be needed at some point in the future. The panel also felt that the field is not yet at the stage of needing a Sematech-like organization around quantum for tool development.

(5) The panel agreed that **hubs and partnerships between academia, US government labs and industry are important** for further progress to be made. Given the clear challenges remaining in scaling up and in improving qubit coherence, "locking in" fabrication technology would be premature at this time, even for foundry services. Given the disconnect between innovation which requires trying new processes and needing to provide reproducibility with dedicated tools, both foundries and user facilities are needed to play these separate roles. Government and academic labs are particularly important to ensure key innovations reach the public domain since industry will not disclose trade secret information.

5.3. Session 2: Spin Qubits (Steven Koester, Chair)

5.3.1. Overview presentation

The second session overview presentation was given by Prof. Mark Eriksson (UW-Madison) (Figure 5). Dr. Eriksson provided an overview of the spin qubit field, with a focus on group-IV quantum spin qubits created in quantum dots formed by electrostatic gating. He noted that, like transmons, spin qubits behave like artificial atoms, but are much smaller in physical size, approaching that of natural atoms.

Importantly, Dr. Eriksson motivated why Si is currently being investigation for spin-based quantum computing, namely its lack of nuclear spins in isotopically pure material. However, he noted the many challenges, including the valley degeneracy, heavier mass, lack of DX centers, and requirement for relaxed buffer layers and strained epitaxy. Among these challenges, Dr. Eriksson indicated that valley degeneracy has proven the most difficult to solve, and that despite progress, this remains a key outstanding challenge. Finally, he also highlighted that other spin computing platforms are being investigated such as Si MOS, Ge quantum dots, and individual P atoms.

Figure 5. Overview speaker slide for session 2: Spin Qubits.

Dr. Eriksson's main takeaways were as follows:

(1) **Si-based spin qubits are extremely promising due to their ability to use the Si processing** backbone for process optimization.

(2) **Charge noise is a key limiting factor** in spin qubit systems and further research on the source of charge noise from defects is needed. **Valley splitting** is also a critical issue that needs to be addressed, and while promising progress has been made, a perfect solution remains elusive.

(3) Due to their small size (~40 nm), lithographic and **interconnect challenges are considerable** for spin qubits in Si. Therefore, novel approaches need to be developed, including using more "CMOS-like" fabrication approaches, particularly for interconnects.

5.3.2. Panel session #2

Panel #2 was on spin qubits and the panelists consisted of Mark Eriksson (UW-Madison), Thaddeus Ladd (HRL Laboratories), Arne Laucht (Diraq) and Dominik Zumbühl (University of Basel). (Figure 6). These panelists had expertise in the different spin qubit platforms, including Si/SiGe (Eriksson and Ladd), Si MOS (Laucht) and Ge (Zumbühl). Each panelist was asked a specific question aimed at their unique expertise in these areas. The questions were aimed at understanding the benefits of the various spin qubit platforms and the fabrication challenges for qubits and interconnects. The responses have been summarized below, where the consensus or majority opinions of the panel are represented.

Figure 6. Contributors for panel session 2: Spin Qubits.

The primary conclusions from panel #2 (spin qubits) were as follows:

(1) For spin qubits, **fundamental work on materials and interfaces remains essential**, particularly to address the problems of disorder (interfaces, alloys, random charges, non-isotopic purity), charge noise, and valley splitting.

(2) **"Yield" is currently a major limiter to upscaling spin qubits. The small size of spin qubits leads to** quantum sources of noise that simply do not arise in CMOS. Further innovations in precision lithography and reducing disorder are needed to address this issue.

(3) Innovations in lithography to improve precision without introducing charge disorder or defects would be very beneficial. **Developing ways to access state-of-the-art optical lithography in an economical way** could also speed development for university.

(4) I**nterconnects for spin qubits are challenging given the density requirements**, but most likely will be driven by economics, such that innovations will only happen once the demand for solutions is sufficiently pressing. Having dedicated foundries to develop this technology, could help to alleviate cost concerns, **though interconnect scaling will not be a focus of extensive investment until spin-based quantum computing becomes more mature**.

(5) **More "CMOS-like" thinking is needed** about how to approach fabrication challenges and optimize processes. At the same time, figuring to make quantum-specific processes available in a CMOS fab (such as the interstitial gate) would also be beneficial. Modifying CMOS processes to reduce disorder and noise will also be necessary, as is developing ways to compensate for disorder that cannot otherwise be removed.

(6) **The funding landscape is often inadequate for addressing many of the challenges facing spin-based qubits.** Many of the materials science issues that need to be addressed, such as Si/SiO_2 disorder, are not seen as sufficiently innovative to garner funding. For instance, obtaining a grant to optimize a simple oxide with low charge noise is very difficult. More focus on these types of "mundane" issues is needed to advance the field. Engagement between experts in the quantum and interface communities may be helpful in this regard.

(7) The LPS Qubit Collaboratory (LQC) has helped to provide qubits through various foundry services, including the **Qubits for Computing Foundry (QCF).** Finding additional ways to leverage foundry services to advance fundamental research will be beneficial.

(8) Research into **ways to integrate control electronics on-chip** without generation of excess heat and noise would be beneficial.

(9) Making user facilities available for quantum device characterization is a difficult challenge. For instance, doing so would require standardization of control electronics. One possibility that was discussed would be to have **pre-characterization (e.g. at 4.2 K) available as a service**, while leaving dilution refrigerator measurements to the individual laboratories. A dedicated meeting or conversation about the characterization needs of the community would be useful.

(10) The panel agreed that **different spin qubit platforms present different challenges.** For MOS qubits, the smaller dot-to-dot pitch (~ 2× smaller than Si/SiGe) leads to more demands on lithography and control of charge disorder. Therefore, it is important to develop ways to minimize disorder at the Si/SiO_2 interface. MOS qubits may require a complete re-evaluation of the materials that exist in the foundry process to identify sources of noise and disorder.

(11) MOS geometries that provide even stronger confinement (e.g. finFETs) have the benefit of allowing higher temperature (e.g. 4.2 K) operation, but **MOS qubits present even greater fabrication tolerance challenges** due to the tighter dimensional control needed.

(12) **Hole qubits have the advantage of not having valley degeneracy**, minimal interaction with nuclear spins, and the ability to be manipulated without a micromagnet due to spin-orbit coupling. Alloy disorder and dislocations are potential problems for scale up.

5.4. Session 3: Color Centers and Optics (Steven Koester, Chair)

5.4.1. Overview presentation

The third session overview presentation was given by Prof. Kai-Mei Fu (University of Washington) (Figure 7). Dr. Fu provided an overview of the optical qubit and color center field. In her presentation, Dr. Fu said that the primary application area for color centers is quantum networks. Quantum networks can fall into 2 different application areas. Very long edge networks for communication and then short edge networks for distributed quantum computing, which could even exist on single chip or package.

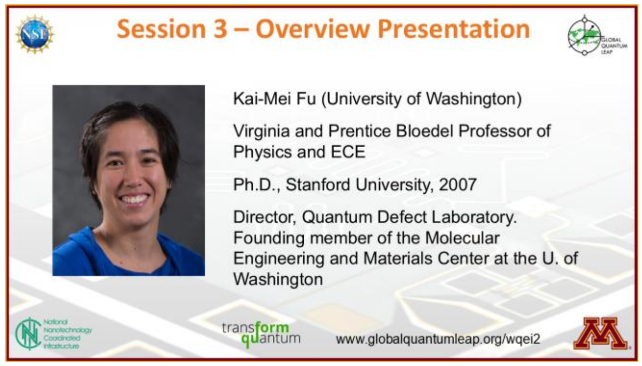

Figure 7. Overview speaker slide for session 3: Color Centers and Optics.

Dr. Fu noted that like other qubits, color centers act as artificial atoms, despite that fact that they are often associated with the absence of an atom, such as with the nitrogen vacancy center in diamond. She compared this system with trapped ions, and said the advantage is that it involves a solid-state matrix, as opposed to ions or atoms being suspended. Like trapped ions, color centers can have similar or even better coherence times.

Amongst the biggest challenges for color centers are homogeneity and scaling. Defects need to be identical to scale effectively. She described how the community is attacking the homogeneity problem differently, either using materials innovation (trying to make them identical from the beginning) or active tuning and control. Another avenue for research is the discovery of new defects, which may have better properties.

Dr. Fu's main takeaways were as follows:

(1) **Fundamental innovations are needed to address homogeneity in color centers.** This needs to occur both through materials and process innovation, to minimize the requirements for active tuning of individual qubits.

(2) **There is a need for infrastructure to better control defect formation**. The standard ion implantation for vacancy creation is not sufficient for exploring new areas due to the material requirements and cost considerations. Current user facility services (e.g. Sandia's Ion Beam Laboratory) is often over-subscribed with long turn-around times.

(3) **A need exists for innovative annealing technology.** The atmosphere for annealing can greatly influence color center properties. There is also a need for both "clean" and "dirty" systems where clean systems can be used for mature technologies where the defect is well understood, and dirty systems can be used to allow novel materials to be introduced.

(4) **Innovations are needed in etch technology.** Both FIB and RIE systems are important, and both clean and dirty systems are needed. Newer techniques such as atomic layer etching, in combination of atomic layer deposition, are especially promising, because they allow nanometer-scale precision, and can help to control and passivate surfaces.

(5) **Color centers have specialized lithography needs.** In addition to electron-beam and optical lithography, focused ion beam lithography is needed, and is particularly useful for rare earth dopants.

(6) **Expertise for process staff is vitally important.** Staff that have the bandwidth to work in process development, go to conferences, and can assist with tool development are needed to accelerate the field.

5.4.2. Panel session #3

Panel #3 was on color centers and optics and the panelists consisted of Kristiaan De Greve (IMEC), Greg Fuchs (Cornell), Neil Sinclair (Harvard), and Gary Wolfowitcz (Photonic) (Figure 8). These panelists had expertise in the different optical qubit platforms, including diamond and SiC (Fuchs), Si (Wolfowitcz), and $LiNbO_3$ (Sinclair). In addition, Dr. De Greve represented the industry technology transfer perspective based upon his position at IMEC. Each panelist was asked specific questions aimed at their unique expertise to help describe the various optical qubit platforms and their fabrication challenges. The responses have been summarized below, where the consensus or majority opinions of the panel are represented.

Figure 8. Contributors for panel session 3: Color Centers and Optics

The primary conclusions from panel #3 (Color Centers and Optics) were as follows:

(1) **There continues to be a need for a diamond "foundry service,"** as it is currently difficult to obtain high-quality diamond and having a steady, reliable supply would be beneficial to the community. Currently, only one company grows the kind of commercially available quantum grade diamond needed for research.

(2) There was also a consensus that **the field needs to strike a balance between reliable foundries and flexible user facilities.** The field is too nascent to down-select at the moment. Therefore, it is important to maintain both government facilities which can act as foundries and universities to provide user facilities for color center research.

(3) Work on novel color centers does not have the benefit of "piggybacking" on CMOS as with other platforms, and **requires more specialized infrastructure.**

(4) **Facilities for fast-turnaround characterization of color center defects is very important,** with more integrated tools to reduce cycle time required. For instance, optical characterization tools with a wide range of wavelengths of excitation and collection would be useful. Quantum level characterization of defects at the wafer scale (e.g. a photonic cryoprober) would be extremely helpful to vet process details and analyzing them at scale.

(5) **The panel felt that the academic community should continue exploring all material pathways for color centers** (e.g. diamond, SiC, Si, etc.) as it is too early to rule out any options at this point. Each platform has a general trade-off between quality of the defects and availability of the material. Diamond has the most well-understood defects, but is expensive, and hard to obtain large wafers. SiC is available in large wafers and the defects are similar with those in diamond. Silicon is promising but still emerging due to its narrow bandgap.

5.5. Session 4: Emerging Platforms (Vlad Pribiag, Chair)

5.5.1. Overview presentation

Figure 9. Overview speaker slide for session 4: Emerging Platforms.

The fourth session overview presentation was given by Prof. Sergey Frolov (University of Pittsburgh) (Figure 9). Dr. Frolov provided a summary of the different categories of qubit research, and contrasted the status of the "emerging" concepts such as topological qubits, with the more standard transmon and spin qubits. Dr. Frolov reviewed the field of topological qubits based upon Majorana zero modes using hybrid semiconducting/ superconducting systems. He noted the main point is that, in reduced dimensions, Majoranas are predicted to be non-Abelian, so they can be detected when their positions are exchanged. This "braiding" concept can be used to store quantum information, and offer protection against noise. However, he noted the challenges of uniquely identifying the existence of Majorana's, which can often cause them to be confused for other phenomena. He also highlighted the further challenge of achieving quantum computing functions, such as braiding, in these systems, and that even achieving to this level of complexity in emerging material systems is challenging.

Dr. Frolov's main takeaways were as follows:

(1) **Topological qubits are still in a very early stage of understanding, and so it important to investigate multiple concepts**, since it is too early to identify a "winner" at this early stage. Even for qubit concepts that do not prove to be practical, the underlying fundamental physics that is learned could still be very useful. However, due to the profound impact of having a qubit that is protected from decoherence, the risk is worth the reward.

(2) Realization of an experimental system that closely resembles theoretical predictions is critical, and **it is an immense materials and fabrication challenge to create a sufficiently ideal system to realize Majoranas**. Therefore, infrastructure to allow ultra-clean interfaces (e. g in semiconducting/superconducting systems) and *in-situ* process are critically needed to minimize disorder.

(3) **Co-location of people and facilities is important** for topological quantum computing studies, since it can be a challenge to have samples travel to and from many labs to complete a fabrication run.

5.5.2. Panel session #4

Panel #4 was on topological qubits and consisted of Sergey Frolov (University of Pittsburgh), Chris Palmstrøm (UCSB), Javad Shabani (NYU) and Christoph Stampfer (RWTH Aachen). These panelists had expertise in the different emerging qubit platforms and materials, including topological qubits (Frolov and Shabani), semiconducting/superconducting materials (Palmstrøm and Shabani) and 2D material qubits (Stampfer). Each panelist was asked specific questions aimed at their unique area of expertise, and were aimed at understanding the benefits of the various exploratory materials platforms and qubit types, with an emphasis on the materials and fabrication challenges. The responses have been summarized below, where the consensus or majority opinions of the panel are represented.

Figure 10. Contributors for panel session 4: Emerging Platforms.

The primary conclusions from panel #4 (Emerging Platforms) were as follows:

(1) **Customized infrastructure is needed to create the atomically-clean interfaces and surfaces** required for topological qubit studies, including selective-area growth, *in-situ* processing, and wafer bonding are all possible methods. "Bottom-up" processes where as much *ex-situ* processing is eliminated could be particularly beneficial.

(2) When cases where *in-situ* processing cannot be used, **there is a need to develop reliable techniques such as etching that reduce damage** and enable control of surfaces and interfaces. Exquisite process is critical to avoid creating systems with too many free parameters.

(3) Exfoliated van der Waals materials are important for advancing emerging quantum research due to the ultra-clean surfaces and interfaces that they can enable. **Improved automation and tool development for locating and manipulating exfoliated van der Waals materials is needed to improve reproducibility.**

(4) **Co-located resources need to have a complete set of researchers and equipment to create a tight feedback loop** of growth, fabrication, and test. Funding to create such local clusters would be helpful.

(5) **Protocols to allow sample sharing to verify results would be helpful** to advance research.

(6) **Improved techniques to verify material and interface quality at an early stage of device fabrication** need to be developed to avoid wasting time and resources. This is particularly important for less common materials (e.g. BiSe, PbTe). For instance, two wafers grown in a row might be unintentionally different, and it can often take weeks to realize that a problem has occurred.

(7) **Semiconducting/superconducting materials are of broad interest** beyond topological quantum computing. Other novel devices such as gatemon qubits, Josephson field-effect transistors, and quantum sensors can use this platform.

5.6. Wrap-Up Discussion (Steven Koester, Chair)

After the workshop, a wrap-up session, moderated by Steven Koester, was held to attempt to capture some of the main outcomes form the workshop. This discussion produced some additional general recommendations for quantum infrastructure.

(1) In general, from an infrastructure point of view, mature technologies benefit the most from access to fabrication foundries, while more emergent technologies need more of the user facility approach. However, **for all qubit platforms, user facilities have a role to play**.

(2) Materials supply is similar to fabrication, in that **the user community could benefit from more consistent supplies of quantum-relevant materials** such as diamond, SiC, and others, particularly from domestic sources. However, material supplies associated with user facilities are still needed to allow exploration of novel concepts.

(3) **Focused equipment funding programs would be helpful**, particularly without additional requirements (e.g. education and outreach). In addition, coordination of the MRI program with national infrastructure programs such as NNCI could help to ensure equipment resources are used to advance research in the most efficient and effective way possible.

(4) Given the limited funding, **improved coordination between agencies** could help to ensure resources are used as efficiently as possible. While DoD and DoE provide significant funding, cross-agency coordination with NSF could help to ensure the best possible infrastructure decisions are made.

(5) While co-located resources are generally beneficial, **a need still exists for enhancing collaborations between facilities.** Therefore, equipment and standardization to allow clean sample transfers between facilities would be useful. This includes vacuum "suitcase" concepts, standard chip carriers, and vacuum transfer interfaces on toolsets. Vacuum transfer within a fab between different tools could also be very beneficial. Government-level coordination between facilities (e.g. through NNCO) may also be needed.

6. Assessment of Recommendations from 2021 WQEI

6.1. Introduction

Based upon the outcomes detailed above, a summary of was assembled regarding how WQEI2 addressed the recommendations from the first Workshop on Quantum Engineering Infrastructure in 2021. Below, the 2021 recommendations are listed, along with a short summary of the progress that has been since 2024.

6.2. Value of NNCI

QWEI1 recommendation 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.

- There is a clear consensus from WQEI2 that user facilities supported through national nanofabrication infrastructure programs such as NNCI continue to be highly valuable for quantum research.

6.3. Need for Flexibility of Infrastructure and Support for Mature Platforms

QWEI1 recommendation 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.

QWEI1 recommendation 3: 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.

- These issues were discussed at length at WQEI2, and the general feeling is that this can be addressed through hubs and partnerships between academia, US government labs, and industry. Some of this occurring today, for instance through the Qubits for Computing Foundry (QCF), though more needs to be done. While it was generally felt that user facilities such as those supported through the NNCI are not well-suited to provide foundry-type serves, they sometimes need to have dedicated "clean" tools for critical process steps, while also having "dirty" for novel concepts exploration. This particularly true for emerging concepts such as topological qubits, where highly customized tooling is needed.

6.4. Materials Supply

QWEI1 recommendation 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.

- This need remains, and it is particularly relevant for color center materials such as diamond. While some progress has been made on the available of Si/SiGe materials through the QCF, more work is needed for "foundry" type supply of materials, while still maintaining availability of flexible material supplies in university labs.

6.5. Characterization

QWEI1 recommendation 5: 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 to speed research progress.

- This need remains as well, though several innovative proposals were suggested at WQEI2. In particular, development of a common platform for cryogenic pre-testing (e.g. at 4.2 K) was suggested, which could help to speed device screening for dilution refrigerator measurement. In addition, the idea of co-locating resources so that a complete set of researchers and equipment are located at single institution could create a tight feedback loop for device innovation.

6.6. Maintaining Process Knowledge

QWEI1 recommendation 6: A mechanism for developing and maintaining process knowledge among process staff is 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.

- It does not appear that significant progress toward this goal has been made, though the need for experienced, knowledgeable staff was re-iterated in WQEI2. Suggested solutions such as a "fellows" program or common process database still have not been implemented, but interest remains to do this.

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