Cover Sheet

Responding to the RFI for Qubits for Computing Foundry (QCF) W911NF-20-RFI-QCF

Title, organization: Vice President for Research, NY CREATES / SUNY Polytechnic Institute

Respondent's technical point of contact:
Satyavolu S. Papa Rao, 257 Fuller Road, Albany, NY 12203, (518) 756-7451, spaparao@sunypoly.edu

Respondent's administrative point of contact:
Kim Pietkiewicz, 257 Fuller Road, Albany, NY 12203, kpietkiewicz@sunypoly.edu

Co-Authors:
James Misewich, Brookhaven National Laboratory, Upton, NY11973, (631) 344-3501, misewich@bnl.gov

Steven Girvin, Brookhaven National Laboratory, Upton, NY 11973, (631) 344-7517, sgirvin@bnl.gov

Gabriella Carini, Brookhaven National Laboratory, Upton, NY 11973, (631) 344-3004, carini@bnl.gov

Hong Tang, Yale University, 15 Prospect St, New Haven, CT 06511, (203) 432-4256, hong.tang@yale.edu

Robert Schoelkopf, Yale University, 15 Prospect St, Hew Haven, CT 06511, (203) 432-4289, robert.schoelkopf@yale.edu

Executive Summary: The quantum research and commercialization ecosystem is poised for growth, but is hampered by the lack of an advanced Quantum Foundry for rapid fabrication of at-scale quantum computing chips. A Foundry would free researchers from wasting resources on maintaining troublesome processes on old tools, and being limited by total qubits/chip. However, building a new state-of-the-art fab is expensive and time consuming – it would be advantageous to leverage existing fabrication facilities that can take on the Quantum Foundry challenge. The semiconductor foundry model's attractiveness is due to the expectation that designs sent to the foundry will result in chips that work as intended by the "fabless" designer, when the foundry's Process Design Kits and Design manual are utilized. A Quantum Foundry has to espouse such a methodology. Simultaneously, the Quantum Foundry also has to be responsive to quantum technology shifts and leaps, work with smaller volumes, greater design variety, and follow a strategy to stay relevant and at the cutting edge of fabrication technology. The Foundry should have proven protocols for baseline process reproducibility, rapid but controlled introduction of new materials, and the ability to monitor tools regularly for contamination and particulate defects, as CMOS foundries do. The Quantum Foundry hence has to exemplify both operational discipline as well as research flexibility. The Quantum Foundry should use an open collaborative research model, but should also give commercial entities the required protection for their intellectual property. The Foundry's sustainability will be helped by adding quantum to co-existing R&D efforts in other areas to spread costs. Prior experience in running foundry-like operations will help the Foundry get a running start. The Foundry should have quantum experts on its team to guide its technology development roadmap, and have a robust program for visiting post-doctoral fellows, as well as proactive support and mentoring of entrepreneurs. Such outreach to entrepreneurs can help with the Foundry's sustainability. The Foundry should incorporate partnerships for advanced characterization of the devices, materials and interfaces to provide guidance and information to researchers, and assist in development of their ideas for quantum computing.

Responses to the User or Foundry questions

Topic 2: Potential providers of foundry facilities

1. Foundry program structure:

Foundry type:

i. What model or level of interaction would you find most helpful?

An engagement model that includes collaborative research with academia and national labs as well as one that respects the intellectual property requirements of commercial entities is advisable. The interaction with users of the foundry could be three-fold: (1) Users design quantum computing circuits *utilizing the open Process Design Kits (PDKs)*, and depend on predictable performance (2) Users *utilize the Design Manual* to create new, as yet-untested, variants of qubits and circuits – in either a proprietary or collaborative fashion (3) Researchers *partner with the foundry to develop dramatically new qubits and circuits*, using new materials, designs, coupling methodologies and fabrication technologies in a collaborative research framework. These three engagement vectors, operating in tandem, would allow the foundry users to rely on increasingly refined technology over time, and also for the foundry to judiciously track technology paradigm shifts, and allow the foundry and its users to stay at the cutting edge over the long term.

ii. Which types of foundries are required to meet the needs of quantum researchers?

A foundry strictly following the standard CMOS model could provide predictable, high performance quantum systems, but would be too inflexible for the needs of quantum computing researchers. A typical research lab, on the other hand, would not be capable of tight process control, nor would it have access to state-of-the-art process technology. The Quantum Foundry required now and for the next decade or two would be one that strikes a *balance between research flexibility and operational discipline*.

The Quantum Foundry should have well-defined protocols for the introduction of new materials into the fab, based on technology needs. Such protocols have been tested in the past two decades, as new materials were introduced into CMOS fabs around the world – with contamination monitoring, tool segregation where necessary, and wafer-backside cleans. For instance, the introduction of AlScN as a material for quantum signal transduction from the microwave to the fiber-telecom C-band wavelengths could be carried out in a methodical fashion, as an adjunct to the AlN films that are already under study. In order to accelerate new material evaluations, a quantum foundry should be equipped with an 'annex' or have existing partnerships that can process wafers under requisite cleanroom conditions, and under tool contamination monitoring protocols, so that wafers can be safely exchanged with the main fab for further processing.

The Quantum Foundry would be *scaled to support prototypes and pilot-scale quantities* for 'early user hardware' rather than being a massive high-volume manufacturing fab. The Quantum Foundry would develop a platform that offers a pathway for *efficient technology transfer to commercial fabs* at the right time.

- A Quantum Foundry with a non-profit organizational structure can better *support the growth and security of the intellectual property of the quantum researchers* that are its partners.
- The Quantum Foundry should have access to leading edge facilities for *in situ* characterization, dilution fridges, X-ray nanoprobes, etc., to accommodate this dynamic field.

iii. Should foundries focus on one technology type or be open to general requests across multiple technologies?

- A foundry focused on one material group (such as superconducting qubits, or trapped ion qubits, or semiconductor-based spin-qubits) is more likely to succeed due to its focus.
- It would be still be highly advantageous for the Quantum Foundry to be able to co-integrate 'adjacent' technologies such as photonic circuits for quantum signal transduction. Similarly, the Test, Assembly and Packaging facility associated with the Quantum Foundry would find it useful to enable package-level integration of SFQ circuits, or optical I/O chips, with superconducting quantum computing chips.

iv. Should foundries have quantum dedicated fabrication lines or would multi-purpose tools be sufficient?

- The foundry *should not be solely focused on quantum technology* for many reasons: economic sustainability of the foundry is easier if the fab cost is not solely borne by quantum devices, advances in other fields, and new materials brought on board can be co-opted for quantum purpose, the continued availability of advanced tooling that is subsidized by utilization in multiple areas.
- There might be some specific tools (or even just chambers) dedicated to specific exposed materials in the main Quantum Foundry. 'Mini-cleanrooms' in an annex, or at partner sites, offer a path to speedy evaluation of new materials prior to determining the need for segregated tools.

v. The immaturity of the underlying fabrication processes is a key challenge for developing a foundry for quantum devices, since there may not be a converged and stable process. How can this be addressed? Does the foundry need to include subject matter experts in quantum devices?

- As quantum technologies improve, as they find new materials and new ways to engineer interfaces and new structures, it is necessary to have an agile foundry, but one with continued access to state-of-the-art tools and knowledgeable about supporting multiple programs, and the introduction of new materials. A fab with operational discipline, however, can hasten technology development by allowing experiments to be conducted with high signal to noise ratio, such that high-value experiments can be rapidly completed, with fewer repeats and missteps, or the confidence in the data to terminate needless further investigation.
- As described above, a mechanism for rapid evaluation of new materials in partially or fully integrated quantum circuit chips should be part of the fabric of the quantum foundry, before the new material becomes seamlessly included in foundry operations.

It is very useful for the foundry to include subject matter experts in the design and use of quantum devices – without them, the foundry could waste time developing processes, design manuals, and process design kits that are not what the user wishes to explore or investigate.

User engagement:

i. What procedure is preferred to select users? (e.g. sole contract with the government, separate contract with each user, etc.)

- The foundry would establish default contract language for engagement with academia, with commercial entities, with national labs/government – with allowance for specific language to be updated where necessary and possible.
- Such a structure would permit the foundry to plan ahead towards sustainability of operations after initial funding from the government grant tails off to a adequately small percentage by, say, Year 5.

ii. Are you aware of potential end-users? What observations do you have of the user community? Is there a minimum number of end-users required for a foundry to be viable?

There are multiple existing, potential end-users for a foundry focused on superconducting qubits. Start-up companies such as Seeqc and QCI, would find a foundry useful. It is possible that a foundry could ignite the growth of more 'fabless' companies in the field of superconducting quantum computing. Large companies without access to state-of-the-art fabrication facilities (such as Microsoft) could also benefit. Federal labs like AFRL and NIST could use such a Foundry. Design automation companies like Synopsys, Cadence and Mentor Graphics would use this foundry to develop their layout/design-simulation offerings in the quantum computing area. The user community would find foundry-assisted interactions designed to connect them with potential corporate partners mutually beneficial. Entities like NASA that need superconducting nanowire detectors for cosmology could benefit from such a foundry – since the base processes would be similar to those needed for, say, high kinetic inductance elements in qubit circuits. Similarly, companies like Qubitekk and Photon Spot that need SNSPDs could find this foundry a way to source chips cost-effectively! Companies such as Raytheon, Lockheed Martin and others interested in high-speed superconducting digital electronics, for say, software defined radio, can also utilize the fab.

iii. What is the desired feedback-loop with future potential end-users?

Sharing of characterization data with the fab by researchers (particularly those in academic and national labs), would help improve the robustness of fabrication for future researchers. Direct engagement among the user community can be organized at regular intervals by the foundry to facilitate growth. A Quantum Foundry with a collaborative approach to technology development would embody the 'co-design' concept, with rapid feedback to identify process and material advantages can be fruitfully harnessed in novel device or system designs.

iv. Would you be willing to host graduate students or post-docs, and/or grant them access to the facility and tools?

The foundry could serve as a location where post-doctoral fellows can conduct their research, <u>after</u> getting trained and familiar with the software tools utilized by the Manufacturing Execution System of the fab. Since this can take a few months to gain adequate familiarity, and continued interaction with the fab is necessary to stay abreast of the technology, it is most effective with Ph.D. students or post-doctoral fellows, or visiting researchers with, say, two- or three-year assignments from the partner institution. In a state-of-the-art fabrication facility, physical access to process tools is almost unnecessary since recipes and process flows are created and stored on servers, and downloaded to the tool for processing specific wafers. Hence, training of students and postdocs is more related to understanding the process technology and how various process steps can interact with each other, and how inline metrology tools can be used to good effect for process characterization and improvement. However, analysis of measurement data is an essential function of research, and can be made accessible to accredited partners of the fab, with obligations on speed of analysis so that the wafers can continue to progress speedily through the fab.

v. Are there barriers (other than funding) or concerns that you feel will prevent users from seeking out a foundry service, and if so, what suggestions do you have to mitigate those?

IP considerations are likely to be paramount. It may be helpful to have multiple models of interaction. (a) A faculty member leading a research group might be interested in collaboration to advance a particular design, and would be funded by an agency that needs continued access to the technology, that the foundry could provide. (b) The university researcher might wish to delay public access merely to the point when some of the fundamental answers have been obtained and published (c) A start-up might need to use existing device models provided by the foundry in new circuit architectures that it wishes to keep proprietary. These models can coexist in a fab where appropriate IP walls can be maintained, through appropriate software partitions, and confidentiality agreements.

2. Foundry status:

- Foundry type: Which quantum computing qubit technologies could the foundry support? What types of materials and components could be available to end-users?

The NY CREATES fab at Albany, NY is suited to support superconducting qubits. The availability of 300mm wafer process tools for epitaxial Si and SiGe, as well as EUV lithography tools imply the gate-defined semiconductor quantum dot qubits can also be fabricated – but this work has not been attempted in earnest at Albany due to lack of funding. The NY CREATES team has begun work on Al-based, α-Ta-based, and Nb-based superconducting junctions and interconnects, as well as high-Q damascene capacitors, and ultra-thin film high kinetic-inductance nanowire structures of TaN and NbN. These efforts are supported by either internal or Federal funding, and are being conducted in partnership with researchers at AFRL-Rome, NIST Boulder, U. Maryland, Auburn University, etc. The fab has demonstrated the ability to use 193nm optical lithography for creating photoresist-based Dolan bridges for transmon qubits [1]. The NY CREATES Test, Assembly and Packaging (TAP) facility at Rochester, NY, is already engaged with multiple customers on photonic quantum chips, in addition to electronic and photonic packaging for non-quantum uses.

- What is the current status and capabilities of the foundry? i.e. is the facility ready to receive users now, or are upgrades required?

The NY CREATES facilities at Albany, NY and Rochester, NY can engage with interested users now - though work will be needed to develop an open Superconducting Quantum Process Design Kit (PDK) to embody the 'Foundry' operational perspective.

- Are future upgrades likely to be required to meet the evolving quantum research landscape?

Future upgrades, such as the addition of specific materials (isotopically enriched silicon, or AlScN for integrated quantum signal transduction) or tools (<4 K, 300 mm wafer probing) must always be counted on to further improve the reach of the technology. Improved characterization tools will also be required, as the relationships between processes and device performance get more fully elucidated with theoretical and material defect models.

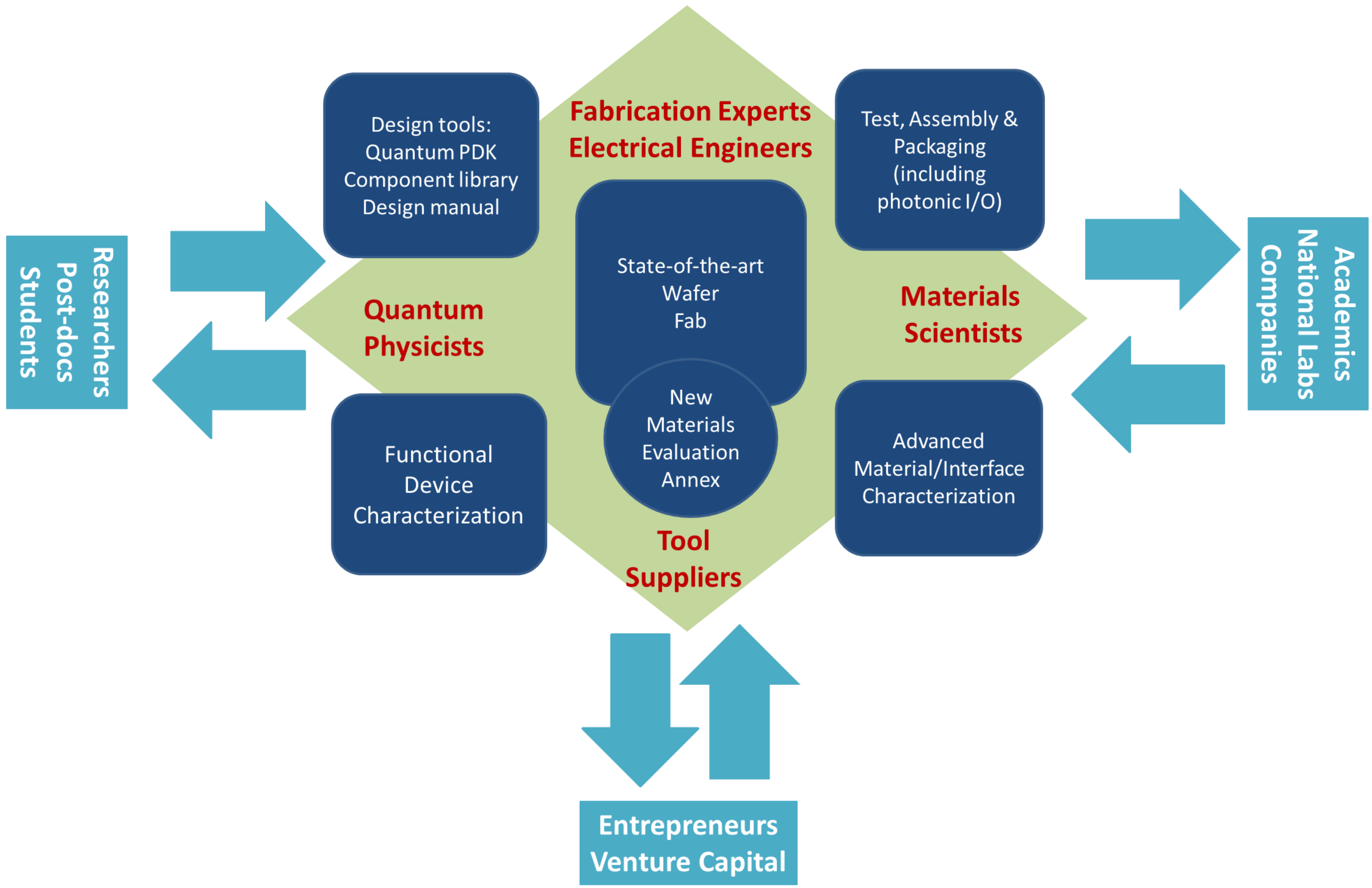
- Are there tools or materials that are hard to find, yet would be useful for fabricating novel or next generation qubits?

3D integration tools at 300mm scale with superconducting materials, and capable of in-vacuum transfer from chamber to chamber will be useful, and currently do not exist.

Citations

[1] "Development of transmon qubits solely from optical lithography on 300mm wafers", N. Foroozani et al, Quantum Science & Technology 4 (2) 025012 (2019).

Overview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Electrical Engineers
Design tools:
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Researchers
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