# Presentation for: DMMI- Materials, Manufacturing and Infrastructure Standing Committee

Broz 3/19-20/2019

# A Few Specific Materials Issues in QIS

Examples and Highlights:

- The QED-C and how it can help
- Materials and Enabling Technologies

Joseph S. Broz, Ph.D.
Vice President, SRI International,
Executive Director and Governing Board Chairman,
The Quantum Economic Development Consortium (QED-C)

March 19th, 2019 DMMI
National Academies of Science

# The Big Picture

- BLUF: There are a large number of materials and manufacturing challenges in QIS and in the emerging "Quantum Industry" (Sensing, computation, communications, metrology)- Overcoming these challenges will have high pay-off.

- The QED-C is an industry consortium focused on identifying technological gaps, closing those gaps, and developing enabling technologies, including materials and manufacturing.

- Steady progress is being made in closing gaps, but resolution of certain challenges would benefit from a coordinated effort and new characterization approaches that potentially include engaging national assets.

# QIS Materials Overview- Summary Snapshot

- There are many materials issues in QIS – These vary dramatically by qubit type(superconducting, trapped ions, photonic, Rydberg atoms, etc.), by application (sensing, comms, etc.), and by device (repeaters, memories, lasers, etc.)
- Materials are critical to QIS performance (e.g. coherence time and fidelity) and to demonstrable quantum advantage in many cases.
- Large gains can be realized from materials engineering and R&D. There is a needed materials science theory, element as well for research prioritization.
- Peripheral and enabling technologies also have major materials issues: In-cryo CMOS or superconducting digital control, photonic interfaces (also cryo), and a host of devices (low-CSWaP, low-T) resonators, attenuators, filters, modulators, switches, combs, etc. Beating Rent's Rule!

# NAS Frontiers of Materials Research: A Decadal Survey (2019)

This snapshot squares with the NAS Decadal Survey:

Key Recommendation: Significant investments by, and partnerships among, NSF, DOE, NIST, DOD, and IARPA will accelerate progress in quantum materials science and engineering, so crucial to the future economy and homeland security.

U.S. agencies with a stake in advanced computing, under the possible leadership of DOE's Office of Science and NNSA laboratories and the DOD research laboratories (ARL, NRL, AFRL), should undertake to support new initiatives to study the basic materials science of new computing paradigms during the next decade. To remain internationally competitive, the U.S. materials research community must continue to grow and expand in these areas.

# The Purpose of the QED-C is:

- To identify gaps and support enabling technology R&D to enhance the quantum "ecosystem": e.g., quantum device components, instrumentation, performance and manufacturing standards, and workforce
- To facilitate industry coordination and interaction with Government agencies
- To provide the Government with a collective industry voice in guiding R&D investment priorities

# How the QED-C can help:

- Many industry members of the QED-C are committed to solving these materials and fabrication problems.
- The QED-C can efficiently connect DOD and industry.
- The “TRL impedance match” is good and can be supported.

# LOI Signatories to the QED-C

- Amazon
- AO Sense
- APS
- ARM
- AT&T
- Atom Computing
- BAE Systems
- Boeing
- Boston Consulting Group
- Bra-Ket
- Caltech/ INQNET
- Citi
- Cold Quanta
- Corning
- CSM
- Entanglement Institute
- Fieldline, Inc.
- GE Global Research
- General Dynamics Mission Systems
- GMU
- Google
- Harris
- Honeywell
- HPD
- IBM
- Intel
- IonQ
- Janis Research
- Keysight
- KLA-Tencor
- Lake Shore Cryotronics
- Microchip/ Microsemi
- Montana Instruments
- NuCrypt
- Photodigm
- Photon Spot
- Psi Quantum
- QC Ware
- QPRI
- Quantum Circuits, Inc.
- Quantum Xchange
- Qubitekk, Inc.
- Raytheon / Raytheon-BBN
- Rigetti
- Rydberg Technologies
- SEMI
- SkyWater Technology Foundry, Inc.
- Stable Laser Systems (SLS)
- SRI
- Toptica
- Vescent Photonics
- Zapata Computing
- Zyvex Labs
- United States Government Representatives NIST and DOE, plus visitors from (ARL, AFRL, OSTP, DOD, NASA, NSF, IARPA, FBI)
- Observers/ Visitors: Lockheed Martin and Northrup; Fermilab

# Quantum Enabling Device Development Continuum

**QED-C Quantum Consortium Activities**

| | | | | | |
|---|---|---|---|---|---|
| **STAGE & TRL:** | **Basic R&D** 1 | **Application R&D** 2 | **Device Prototypes** 3 | **Enabling Component Development** 4 | **Prototype Components and Subsystems** 5 |
| **ACTIVITY:** | Understanding Physical Phenomena | Exploiting & Controlling Phenomena | Create First of a Kind Devices | Create Key Sub-Components & Devices/ T&E/ Performance Stds. | Develop Efficient Common Purpose-Driven Device Designs/ T&E/ Stds. |

**EFFICIENCIES:**

Public/Private Support:
Funding & Collaboration

Introduce New
Common Enabling Devices
Performance Standards

**ENGAGED DISCIPLINES:**

Quantum devices/ Theory / R&D / Materials

T&E / Engineering Design & Development

MATURE INDUSTRY

- **De-risked components**
- **Robust infrastructure**
- **Common standards**
- **Testbeds**

**Competitive R&D And Industry Activities:**

- **Production Equipment Fabrication & Sales**
- **COTS Device Manufacturing & Sales**
- **Full Quantum Systems**
- **Deploy Quantum Systems at Utility Scale**

Create Device Production Equipment Standards

COTS Device & Systems Performance Standards

# BACK-UP Slides

# Specific Example: SC Resonators and Qubits

- Materials R&D is critical to increasing coherence times and gate fidelity (e.g. Al on Si substrates are the “workhorse materials” with Al/AlOx/Al JJ’s)
- SC Resonator (co-planar Al (or Nb)) Q factor provides good estimate of qubit relaxation rate ($T_2, T_1$)
- Some identified materials-related causes of low Q (and likely qubit decoherence):
    - Poor microwave hygiene; On-chip tapered interconnects, sharp geometry, bump-bonds, poor impedance matching (Fano resonances)
    - Coupling to TLS at substrate interfaces: Nanofabrication techniques: photolithography, thin film deposition, and etching leave 1-10 nm thick interfacial dielectric films with large loss tangents
    - Quasiparticle generation in the SC material from stray infrared light, thermal activation (confirmed by 1/f noise in T)
    - Manufacturing inconsistencies
- Packaging and wiring Influences- Stray fields; Eddy currents; Cavity ringdown
- Needed Theory: Full interaction Hamiltonian & Estimates of interaction strength

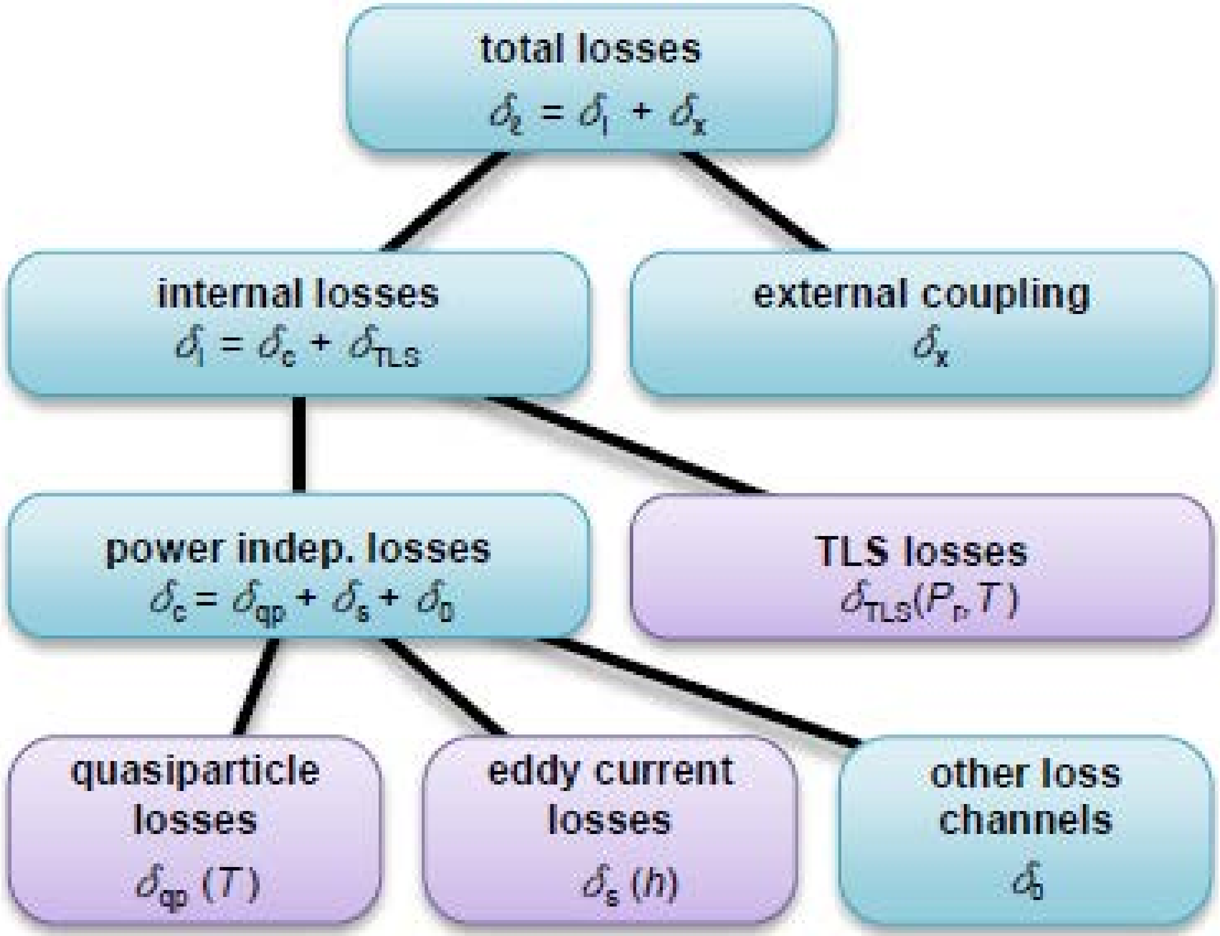
Burnett, et al. Journal of Physics: Conf. Series **969** (2018) 012131

# How might we approach these challenges? (Broz’s view only– not the QED-C’s!)

A modest proposal: The “geneticist’s” approach. Requires coordination among Industry (QED-C), USG, and Academia– *Drosophila model*

- Choose a simple, yet universal, design (either qubit, resonator, or both) to study and use as a base model for ILC. Variables reduction!
- Create a robust theoretical framework for this simple element
- Assess and prioritize loss terms- Rank in magnitude order. Possibly assign certain analyses to certain groups or laboratories. Employ national materials characterization facilities– x-ray and neutron scattering.
- Apply characterization tools and facilities to examine materials and fabrication. (e.g. <u>Deliberate introduction of defect densities</u> for root cause and sensitivity analyses.)
- Analyze range of parameterized models, controlling variables, using ILC’s and correlation to new and novel material characterizations.

# Summary of Loss Mechanisms (Goetz, et al., Jan 2016)



# Summary of Materials and Fabrication Issues

Materials

- Substrates
- Substrate shielding
- RF and phonon management

Fabrication

- Nano and micro fabrication
- Scalability
- Defect reduction
- Epitaxial deposition methods