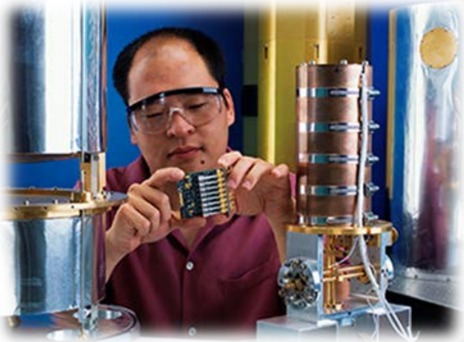
NIST Programs and Vision in Quantum Information Science

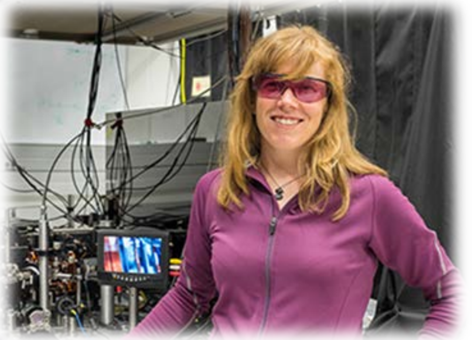
CARL J. WILLIAMS
Acting Director
Physical Measurement Laboratory (PML)
National Institute of Standards and Technology

June 5, 2018

carl.williams@nist.gov



NIST
National Institute of Standards and Technology
U.S. Department of Commerce



PML
PHYSICAL MEASUREMENT LABORATORY

Quantum Information Science in a Nutshell

Quantum information science (QIS) exploits unique quantum properties such as *coherence, superposition*, *entanglement*, and *squeezing* to *acquire*, *transmit*, and *process* information in ways that greatly exceed existing capabilities.

QIS is a field of scientific inquiry in its own right, with applications in:

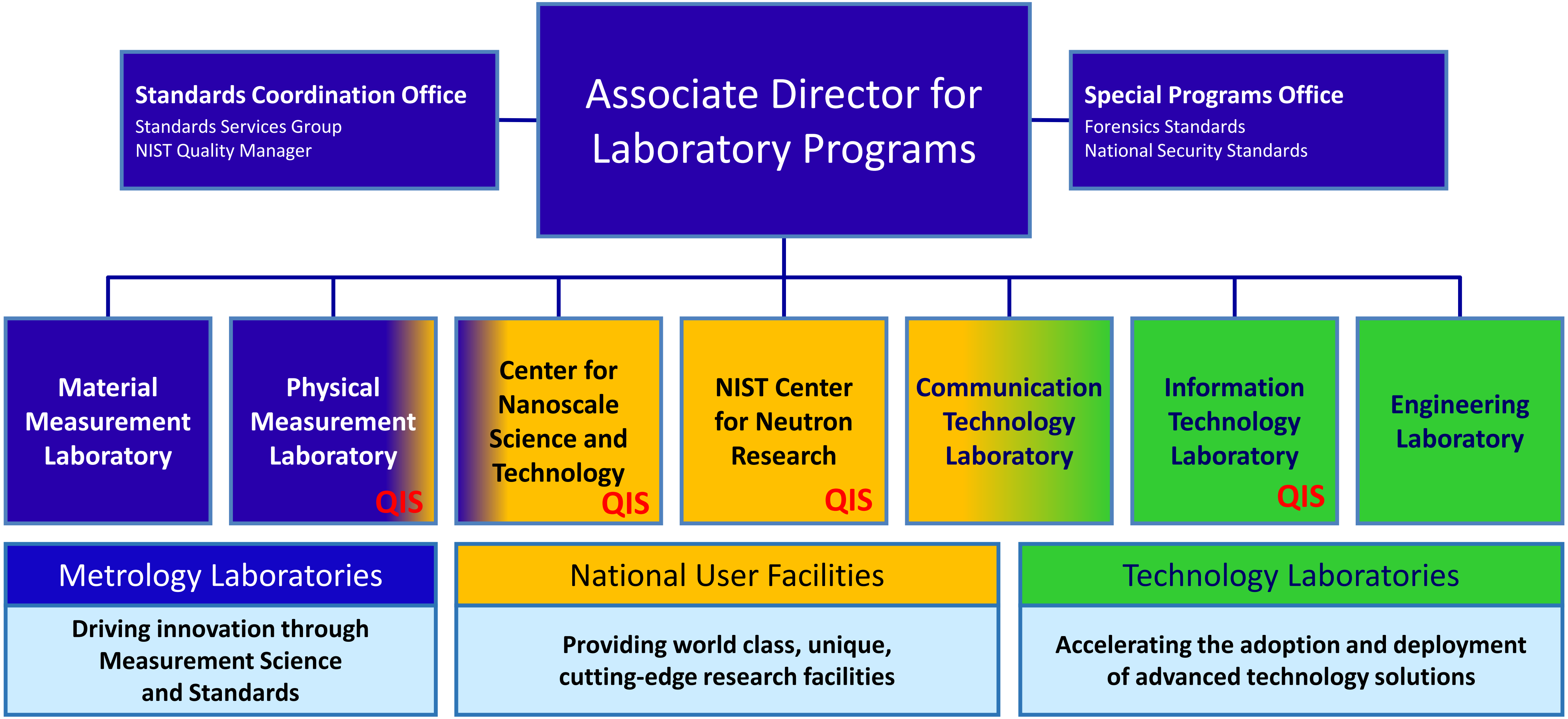
- *sensing and metrology:* precision navigation, timekeeping, magnetic fields, …
- *communication:* secure data transmission and storage, random number generation, …
- *simulation:* complex materials, molecular dynamics, QCD, …
- *computing:* cryptanalysis, quantum chemistry, optimization, quantum field theory, …

NIST's QIS Program covers all of this

and robust intellectual connections to numerous areas of basic research.

NIST program currently focuses on QIS but our activities already include aspects of quantum engineering which must grow!

NIST Laboratories and User Facilities



Standards Coordination Office
Standards Services Group
NIST Quality Manager

Associate Director for Laboratory Programs

Special Programs Office
Forensics Standards
National Security Standards

Material Measurement Laboratory

Physical Measurement Laboratory QIS

Center for Nanoscale Science and Technology QIS

NIST Center for Neutron Research QIS

Communication Technology Laboratory

Information Technology Laboratory QIS

Engineering Laboratory

Metrology Laboratories

Driving innovation through Measurement Science and Standards

National User Facilities

Providing world class, unique, cutting-edge research facilities

Technology Laboratories

Accelerating the adoption and deployment of advanced technology solutions

History of QIS at NIST

- 1992 Wineland suggests spin squeezing for improved sensitivity of clocks
- 1993 Competence project initiated to support idea
- 1994 **First Workshop *ever* focused on QI held at NIST**, Gaithersburg (August 94)
- 1994 NIST starts exploring use of correlated photons for **absolute detector calibration**
- 1995 Cirac and Zoller propose gate based on ion traps
- 1995 Wineland and Monroe implement **first quantum gate**
- **2000 NIST QI Program established**
- 2000 First NIST Quantum Computing Competence
- 2001 DARPA supports Quantum Communication effort
- 2003 NIST QI Program broadened
- 2003 NIST holds *first* Single Photon Workshop
- 2005 First NIST ***Initiative*** for QI is funded
- 2006 Joint Quantum Institute established
- 2012 Wineland wins Nobel Prize for research in support of QIS
- 2104 Joint Center for Quantum Information in Computer Science (QuICS) is established

NIST Activities in QIS

- Quantum Communication:
  - Physical limitations of quantum communication
  - Random number beacons/generation
  - Improved single photon and entangled sources
  - Improved detectors - both high QE and commercially viable
  - Quantum State Discrimination and Optimal Receivers
- Quantum Computation and Simulations
  - Quantum Computing efforts include – Ions, atoms, JJs, Si SETs, P:Si
  - Focus on improved quantum coherence through better trap technology and improved materials
  - Benchmarking and characterization of gates
  - Simulation of iconic condensed matter systems
- Quantum Transduction: Transforming and moving quantum information

NIST Activities in QIS (2)

- Quantum Information Theory and Algorithms
  - Quantum resistant (*post-quantum*) cryptography
  - Power of quantum computation algorithms, complexity
  - Randomized Benchmarking of Gates
  - Quantum Tomography by compressed sensing
  - Understanding what QI says about physics, QM, and the universe
  - Exploration of quantum one-time programs
- Quantum Sensors and Quantum Based Measurements
  - Quantum Logic and Entanglement Based Clocks
  - Super-resolution imaging
  - Quantum limited physical sensors
  - Absolute optical calibration based on photon counting
  - Low noise amplifiers and parametric amplifiers beyond the SQL
  - Improved magnetometry, gravimetry, …

Quantum Information Theory

Characterization / benchmark physical realizations of QI processing

Demos: state preparation, error correction, gate operations, transduction
Quantum state characterization (tomography)
Analysis of Bell inequality measurements
Randomized benchmarking

This is largely joint with PML

Quantum algorithms and complexity

Quantum algorithms for quantum field theory
Adiabatic quantum algorithms
Quantum reinforcement learning

Applications

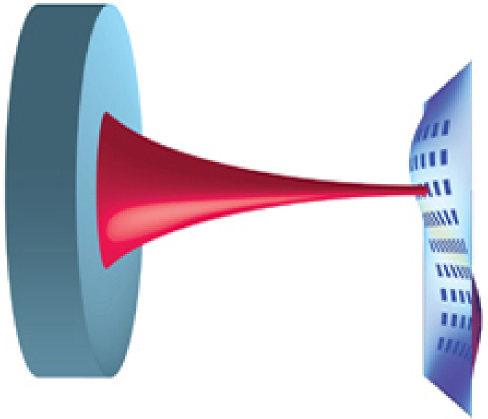
One-time programs/memories based on the isolated qubit model
Random number generation based on Bell inequality violation **– with PML**
Quantum cryptography (key distribution and post-quantum cryptography) **– with PML**

"Hardware" Characterization, Benchmarking

Algorithms, Complexity Theory

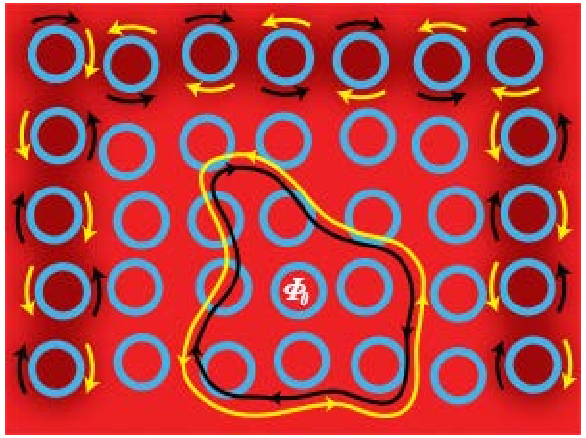
Applications

Quantum Information Science at NIST



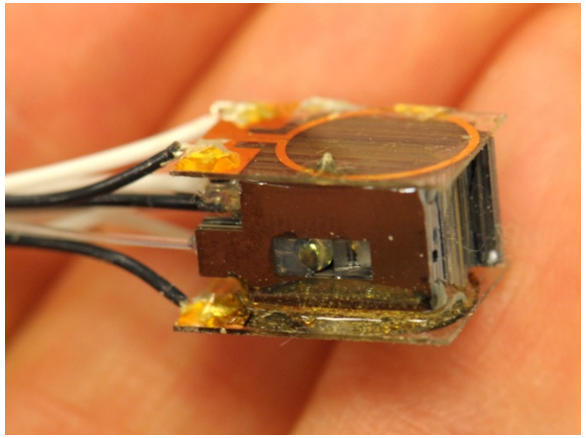
Quantum Transduction

We must realize efficient transfer of information between quanta of different types. Shown here: an optical cavity coupled to a vibrating, mechanical membrane.



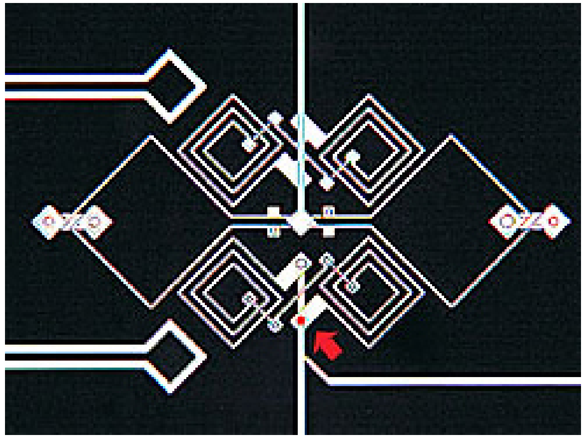
Complex Quantum Systems

We must develop tools for understanding, controlling, and measuring complex quantum systems. Shown here: a photonic chip with ring resonators provides topologically robust transport of photons.



Small Quantum Systems

Small quantum systems will be improved sensors and better standards. Shown here: a chip-scale atomic magnetometer.



Quantum Materials and Solid State Qubits

Solid state realizations of qubits are promising for mass production, though additional research is required. Shown here: a Josephson junction qubit.

Future QIS Activities at NIST

- **Quantum Engineering:** Create the foundation for this new engineering discipline through centers, a QIS consortium, engagement with external partners, and other venues to support innovation and competitiveness;

Applied R&D

- **Quantum Metrology:** Create the metrological foundations essential to the future application of technology arising from quantum information science and engineering both for innovation and for future measurement science;

Basic R&D

- **Quantum SI :** Expand the foundations for a more ubiquitous dissemination of measurement standards based on this technology, whether at a primary calibration laboratory, on a manufacturing floor, in an airplane, or out in the real world.*

Mission Based Delivery

[*] *Quantum SI* was discussed at the October 2017 VCAT so the focus here is on quantum engineering and metrology

NIST Hardware Activities supporting QC

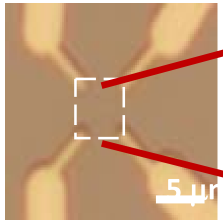
- Hardware efforts include atoms, ions, photons, Josephson Junctions, and P- and B- doped Si
- Current pushes include (***the first 4 are FY18 pushes***):
  - **Strengthen NIST leadership in Quantum Information Theory (with ITL)**
  - **Accelerate the Atom-based Devices for Solid State Quantum Computing**
  - **Create the Metrology for Superconducting Quantum Devices for Quantum Computing**
  - **Develop and Characterize Highly Efficient Components for use in Quantum Information Processing with Photons**
  - **Accelerate metrology in support of Ion Trap Quantum Computing**

Metrology, Materials and Engineering for Single Atom Devices

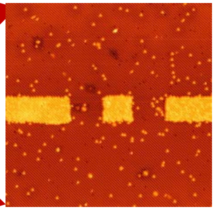
Single Atom Devices

Building the foundation to make, measure, and model atomic devices for future classical and quantum computing. Developing metrology to characterize few atom structures using atomically resolved scanning tunneling spectroscopy, aberration corrected TEM, atom probe tomography, and transport measurements.

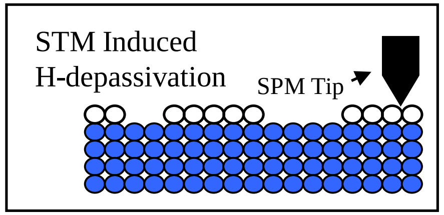
- Scalable solid state architectures for silicon QI
  - Control quantum state of individual electrons
  - Materials that preserve the quantum state of electrons
- Atom technology for ultimately scaled Si electronics
  - Single and few atom transistors
  - Atomically abrupt tunnel junctions
- New materials with designer electronic and optical properties
- Atom technology for embedded on-chip metrology
  - Frequency standards/atomic clocks
  - Charge pumps/current standards
- Quantum simulations and experiments on quantum entanglement with precisely defined atomic structures

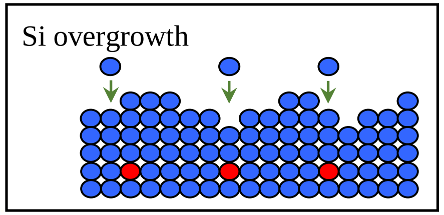


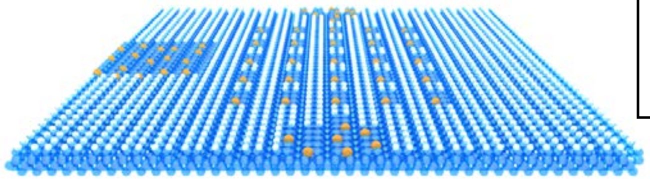
Building an SET for spin to charge conversion



Atomic scale quantum dot with tunnel junctions







Engineering atomically precise materials

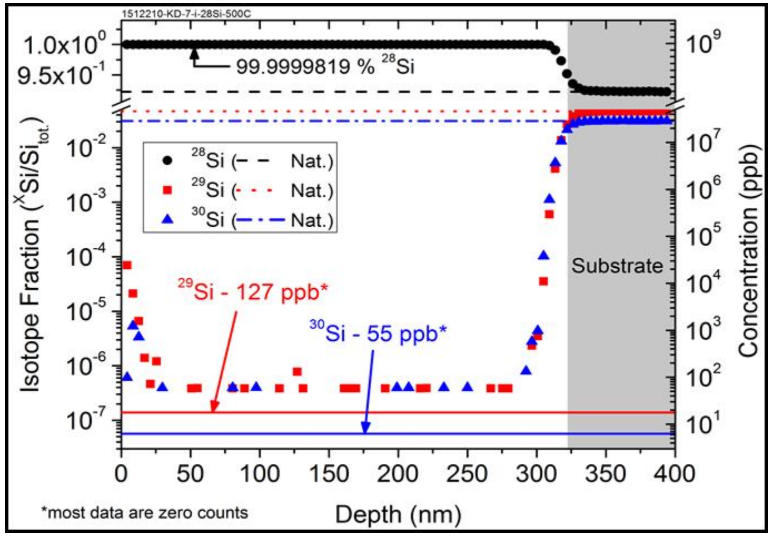
Developing fundamentally new measurements of local electronic states, energy spectra, and electron coherence as well as methods to measure with atomic precision as devices are made.

Enhanced Materials for Atom-based Quantum Devices

BBC News - Purer-than-pure silicon solves problem for quantum tech

Physicists make the purest silicon ever seen, solving a supply problem for research into quantum computers.

Vacuum for solid-state devices



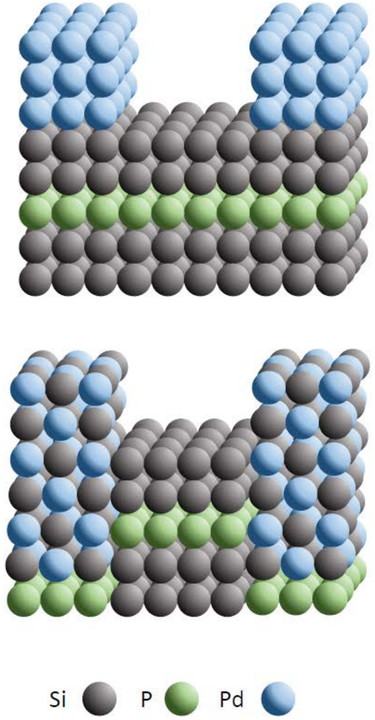
Pure Decoherence free Si

- Isotopically enriched ^{28}Si to 99.99998%

Targeted enrichment

- Standards for decoherence metrology

Contacting dopant atoms in buried layers

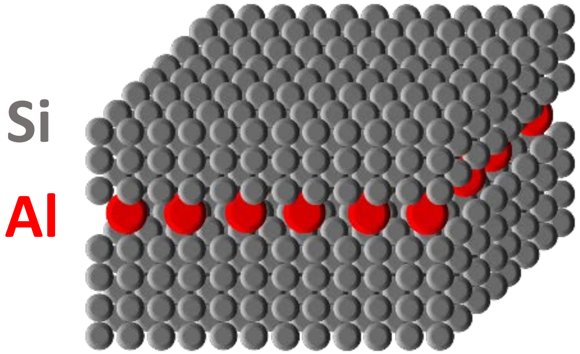


Lithography and Pd deposition

Pd$_2$Si formed @ 250 C

- Yield > 99.9%
- Lowest resistance process known
- No impact on phosphorus pattern fidelity

Semiconducting/ superconducting hybrids

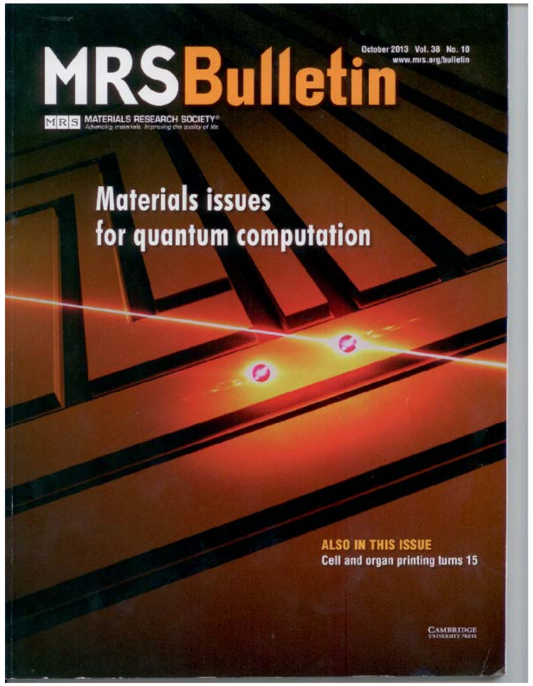


Integrating different platforms in the same atom-based device

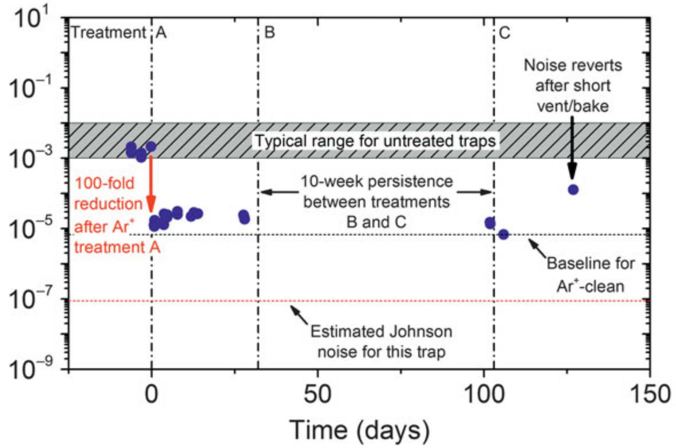
- Al δ-doped Si experimentally shown to be 2d hole gas
- Working to achieve superconductivity in Al 2D layer

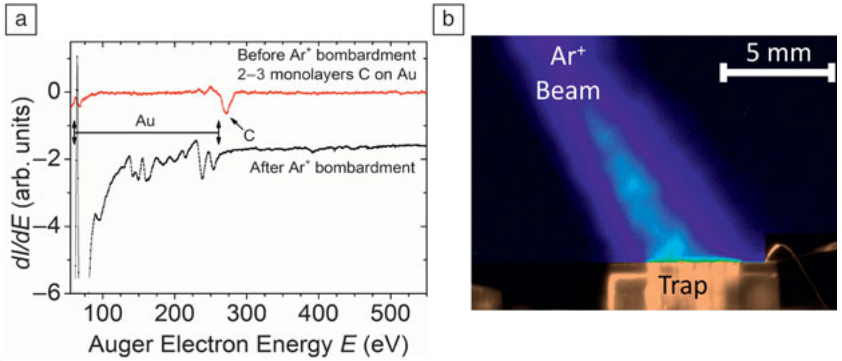
Engineering for Ion Trap QC

Improved Ion Traps for QI



- Integrated Ar^+ bombardment with ion trap to clean the C contamination
- Heating rates reduced two orders of magnitude
- Identified possible mechanisms of heating
- Built stylus trap w/Sandia to characterize different surfaces close to trapped ions
- Built full optics table setup w/surface analysis chamber
- Allows ions to be closer to trap for better control



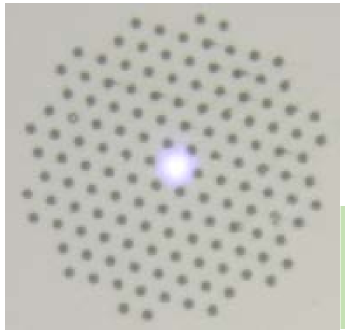


- **Cover of MRS Bulletin on QI, 38,** 830-833 (2013)
- **"100-Fold Reduction of heating rate"** PRL **109**, 103001 (2013)
- **Stylus trap, RSI 84**, 085001 (2013)

NIST UV Fibers Aid High Fidelity Gates

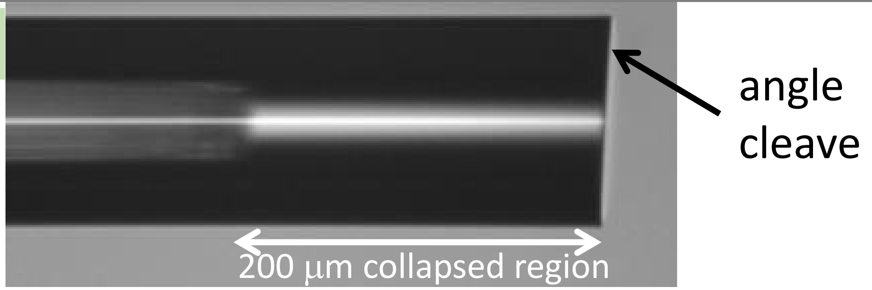
- High power single mode UV fibers developed at NIST (photonic crystal fiber)

Fiber recipe at http://www.nist.gov/pml/div688/grp10/index.cfm

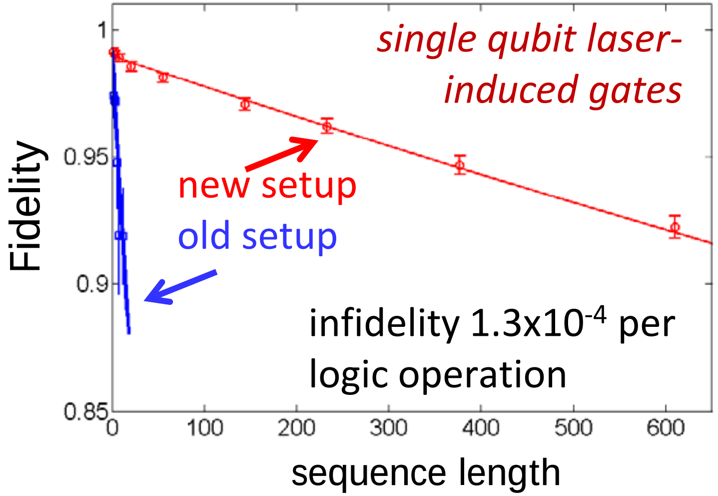


Left: fiber cross section, photonic crystal air holes with UV light propagating in a single mode in the solid core

Right: fiber tip, air holes are collapsed



- Pure fused silica fibers, loaded with H_2 at 10 MPa and cured with UV light
- Wide band single mode (tested at 355 nm, 313 nm, 280 nm), high power (125 mW @ 313 nm), low loss (0.13 dB/m @ 313 nm)

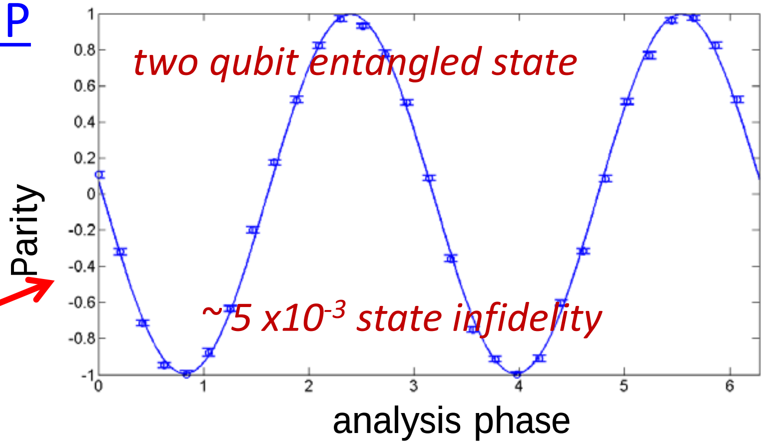


Towards scalable high-fidelity QIP

UV fibers were incorporated in new setup for $^9Be^+$ qubits

Reduced beam pointing instability and improved mode quality

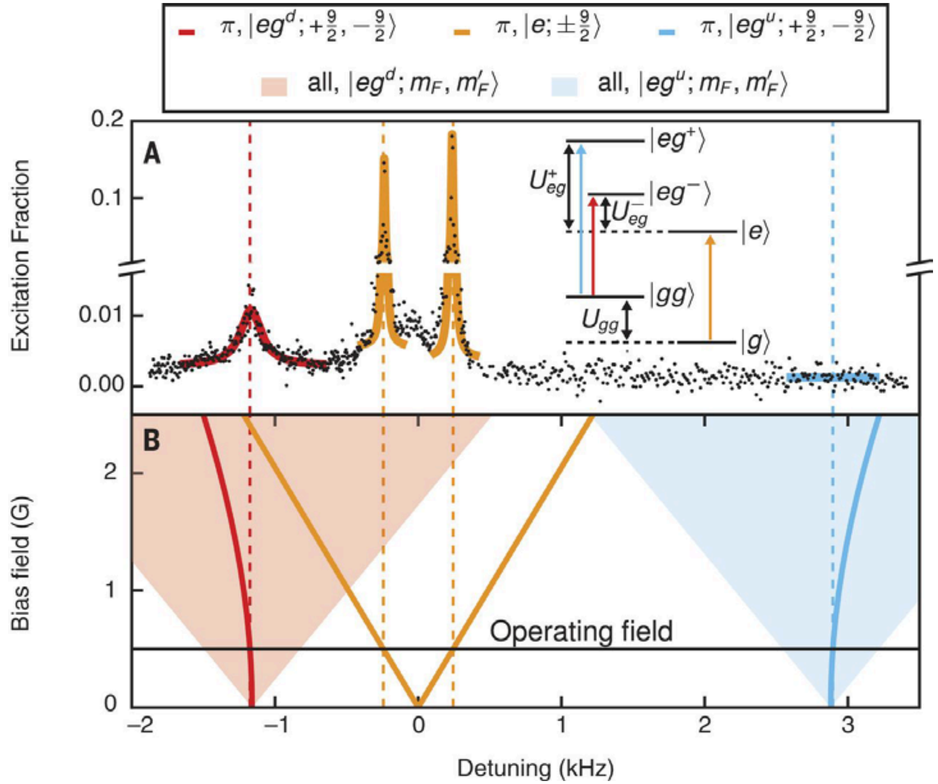
Large improvement in quality of operations



Colombe *et al.*, **Optics Express <u>22</u>,** 19783 (2014**)**

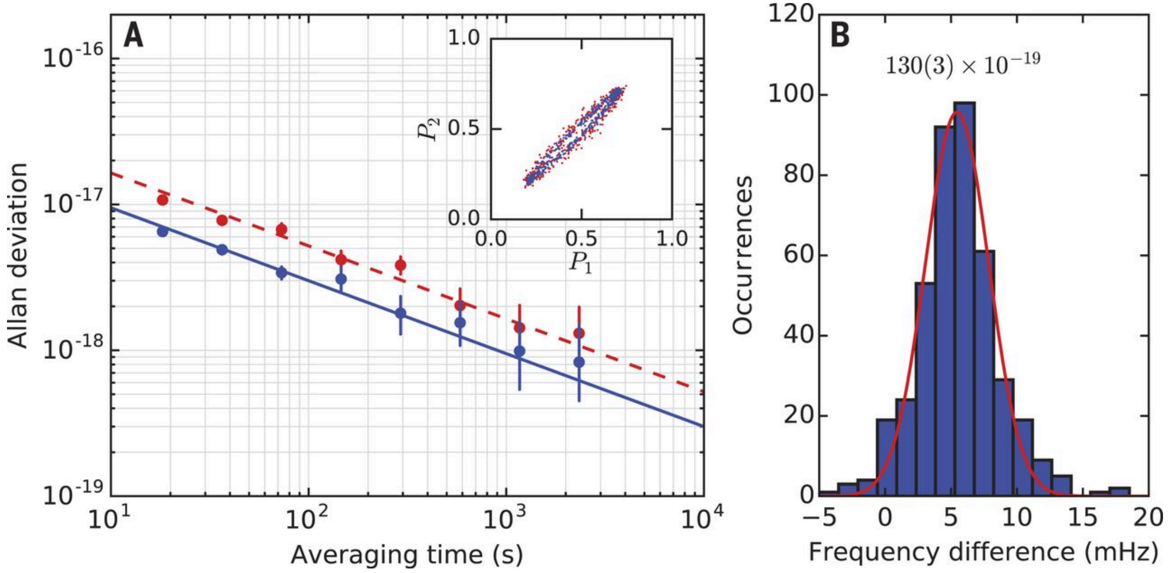
Metrology for Future Atomic Clocks

Sr Fermi-degenerate 3D Optical Lattice Clock



Clock spectroscopy for a two-spin Fermi gas in the m_F = ±9/2 stretched states for a 0.5 G magnetic field – a small fraction of the lattice sites contain both spin states.

- Synchronous clock comparison between two regions of the 3D lattice yields a measurement precision of 5×10^{-19} in 1 hour of averaging time
- **Red** and **Blue** show comparisons of 1000 and 3000 atoms in each region showing a sqrt(3) improvement in stability



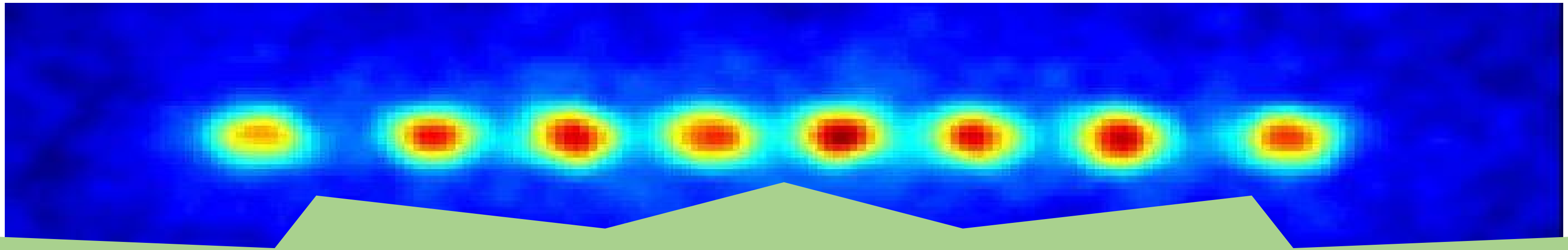
Campbell et al., Science **358**, 90 (2017)

Harness Entanglement to Reduce Quantum Noise

- Operate Al$^+$ clock with N = 5 ions in fully entangled state: Reduced quantum noise

$$\sigma_y(\tau) = \frac{1}{\omega\sqrt{NT\tau}} \quad \Rightarrow \quad \sigma_y(\tau) = \frac{1}{\omega N\sqrt{T\tau}}$$

- Differential excitation overcomes atom/laser desynchronization
- **→ 1x10^{-18} measurement precision in 1 hour! (1000x improvement)**



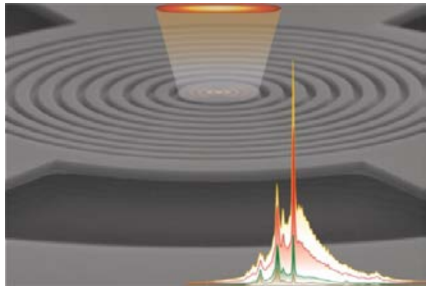
High risk: differential excitation and entanglement have never been implemented in state-of-the-art clocks!

Integrated Photonics: From the Nanofab to Devices, Metrology and Engineering

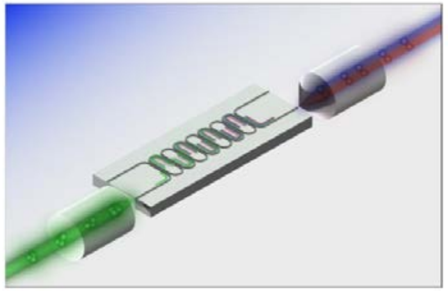
Nanophotonics Laboratory: Kartik Srinivasan

Generating quantum states of light

Quantum Dot Single Photon Source

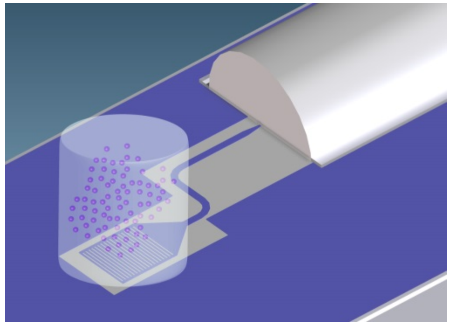


Silicon Photon Pair Source

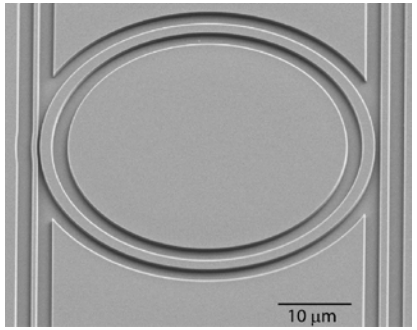


Chip-scale metrology tools

Vapor cell integration

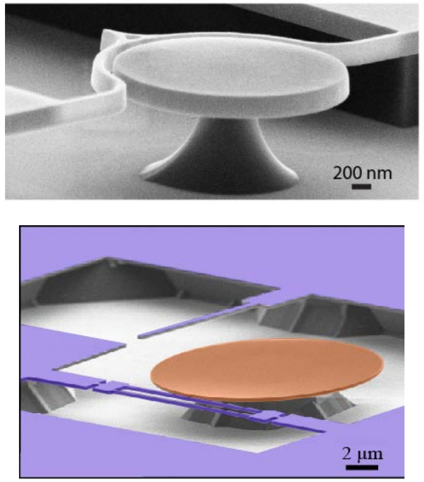


Frequency combs

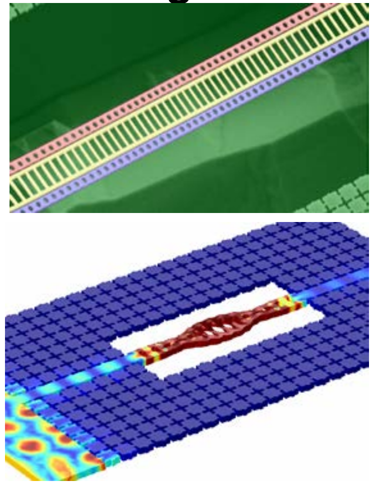


Cavity optomechanical transducers

Force/displacement sensors

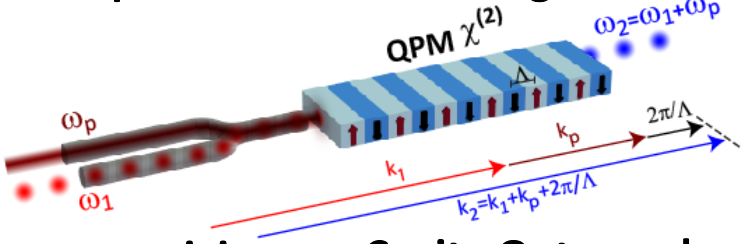


RF/optical/mechanical integration

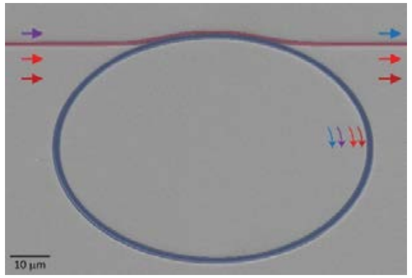


Quantum frequency conversion

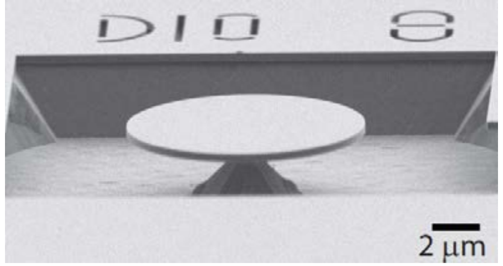
Quasi-phase matched waveguides



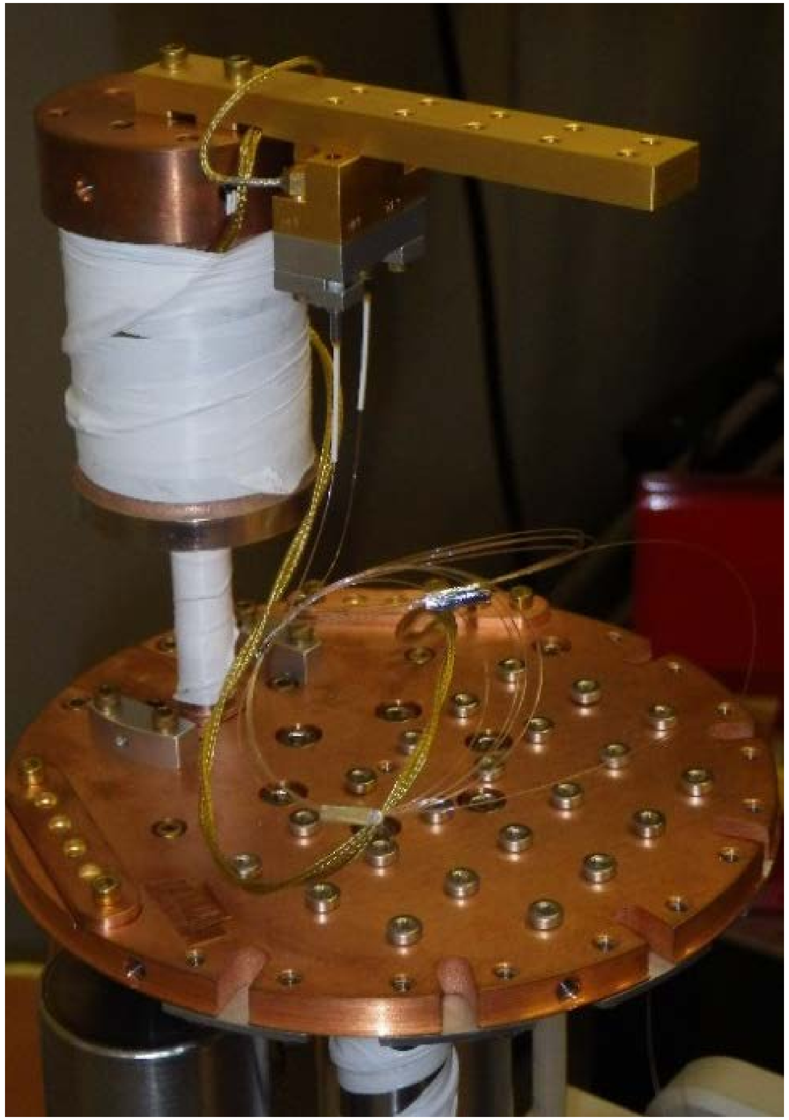
Four-wave-mixing



Cavity Optomechanics

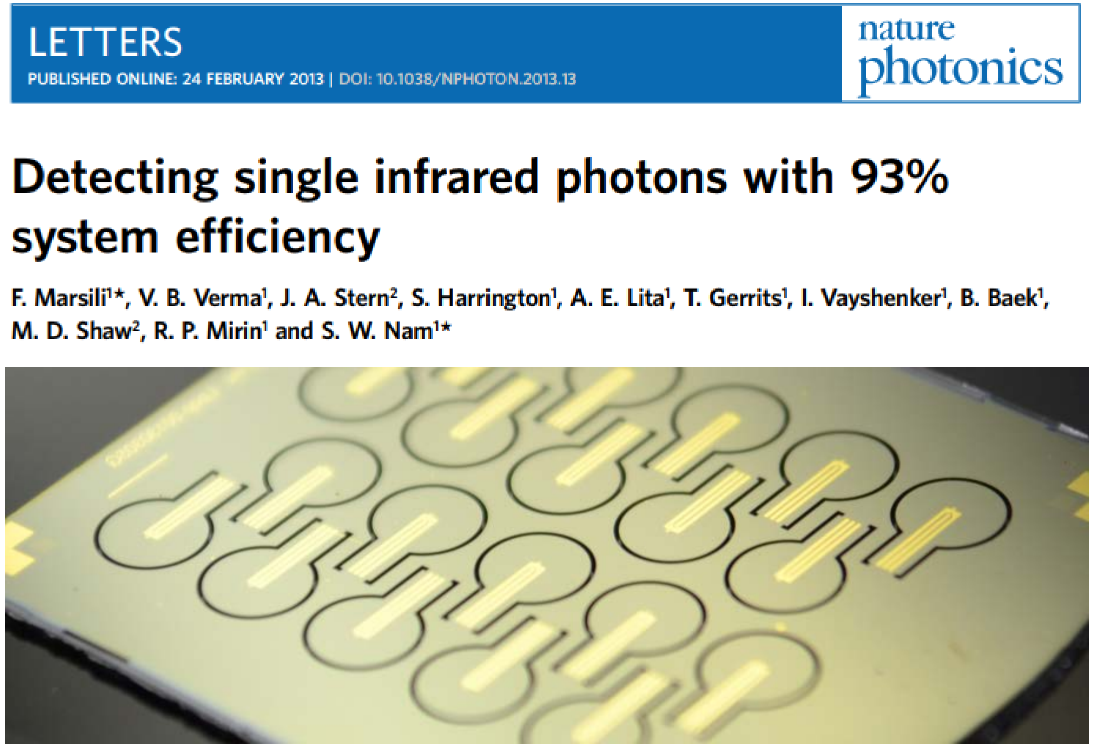


Superconducting Nanowire Single Photon Detectors



Superconducting nanowire single photon detectors from NIST Boulder (V. Verma, R.P. Mirin, S.W. Nam) and Photon Spot (V. Anant)

Si SPADs at 950 nm	SNSPDs at 950 nm
Det. Efficiency = 10 %	Det. Efficiency > 80 %
Timing jitter = 100 ps	Timing jitter = 120 ps



LETTERS

PUBLISHED ONLINE: 24 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.13

nature photonics

Detecting single infrared photons with 93% system efficiency

F. Marsili[1]*, V. B. Verma[1], J. A. Stern[2], S. Harrington[1], A. E. Lita[1], T. Gerrits[1], I. Vayshenker[1], B. Baek[1], M. D. Shaw[2], R. P. Mirin[1] and S. W. Nam[1]*

www.photonspot.com

Discussion

QIS Consortium Concept: Q. Engineering

An organization to allow broad interaction between academia, industry, national laboratories and government agencies.

QIS consortium primary objectives:

- Provide technology forecasting and identify gaps within the QIS ecosystem, including providing overall market guidance;
- Provide an efficient mechanism for strong public-private sector coordination;
- Identify Grand Challenges for the QIS field and explore transformative device technology;
- Identify key technologies that will enable more rapid development of the QIS field;
- Prioritize gaps, grand challenges, and key technology needs that will improve government investments;
- Provide a forum for joint public-private funding of relevant gaps and key technologies;
- Explore novel approaches to cooperative development and technology transfer between consortium members that facilitates rapid technological development;
- Identify the work force needs essential to efficient development of quantum technologies.

Questions for Discussion

What should NIST consider with regard to:

- Is this a reasonable approach to NIST’s future activities in QIS?
- How does NIST determine the correct balance between quantum engineering, quantum metrology, and the quantum SI?
- What new methods for effective technology transfer of emerging quantum technologies should NIST explore?
- Are there new new mechanisms and tools that lower barriers and enhance engagement between government, academia, and industry?
- In a larger quantum engineering effort what should be the role of centers?
- Do you have advice about a quantum consortium?