Impact of Quantum Information Science on the Future of Nanoelectronics

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April 2, 2019

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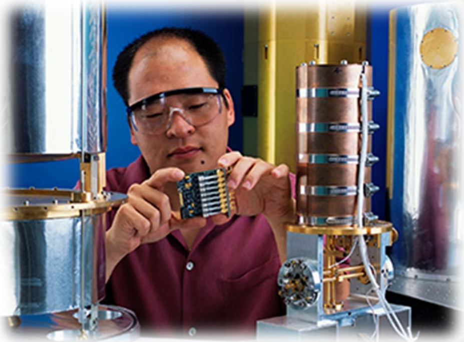

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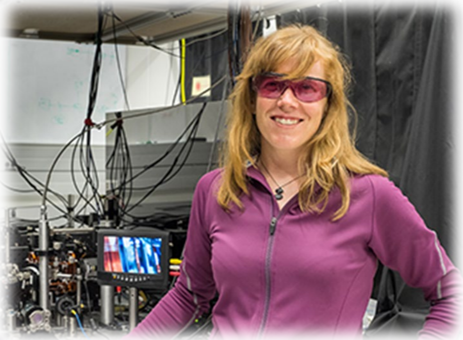
U.S. Department of Commerce



PML
PHYSICAL MEASUREMENT LABORATORY

Key Take Away Points

- Need to build a Quantum Information Science (QIS) ecosystem just as there exists an ecosystem for semiconductors and nanoelectronics
- Natural evolution of semiconductor or nanoelectronics may lead to qubits for quantum computing
- Finally and *most significantly* the most complex semiconductor or nanoelectronics control system ever designed will be the one built to control the *general purpose* quantum computer

What is QIS and is it a big deal?

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.

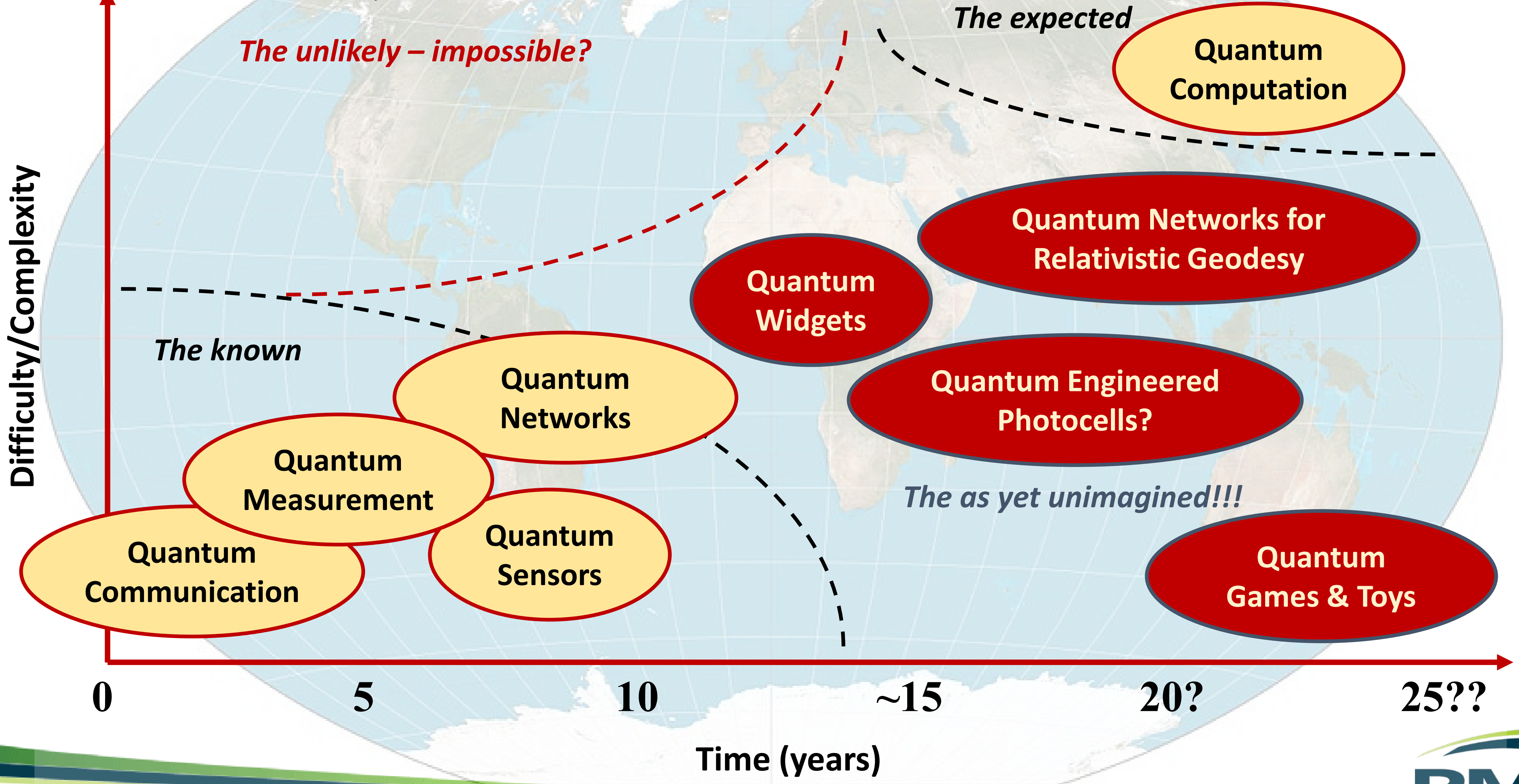
QIS is a field of scientific inquiry in its own right, with applications in:

- *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.

Quantum Information Timeline



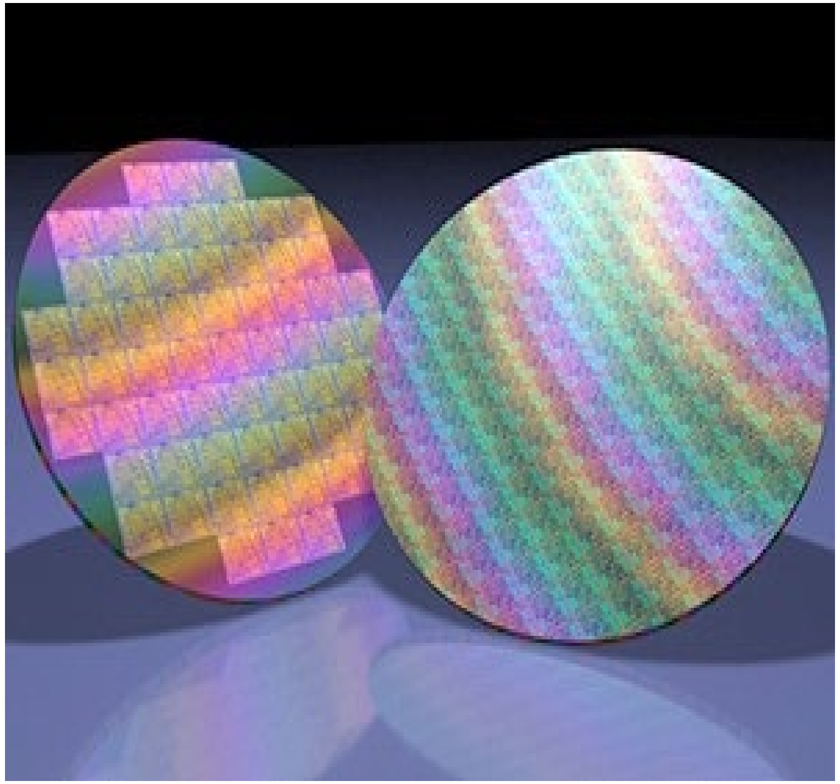
What does it take to build a quantum industry and the supporting ecosystem?

Birth and Development of an Industry

First Transistor, 1947
William Shockley, John Bardeen, and Walter Brattain

INDUSTRY & INFRASTRUCTURE

- Wafer processing
  - Wet cleans
    - Cleaning by solvents
    - Piranha solution
    - RCA clean
  - Photolithography
  - Ion implantation
  - Dry etching
  - Wet etching
  - Plasma ashing
  - Thermal treatments
    - Rapid thermal anneal
    - Furnace anneals
    - Thermal oxidation
  - Chemical vapor deposition (CVD)
  - Physical vapor deposition (PVD)
  - Molecular beam epitaxy (MBE)
  - Electrochemical deposition (ECD)
  - Chemical-mechanical planarization (CMP)
  - Wafer testing
  - Wafer backgrinding
- Die preparation
  - Wafer mounting
  - Die cutting
- IC packaging
  - Die attachment
  - IC bonding
    - Wire bonding
    - Thermosonic bonding
    - Flip chip
    - Wafer bonding
    - Tape Automated Bonding (TAB)
  - IC encapsulation
    - Baking
    - Plating
    - Lasermarking
    - Trim and form
- IC testing



2018, IC (12”, < 10 nm)

Complements J. Broz, SRI

Industry is Investing

- Large Companies are investing: *e.g.* IBM, Microsoft, Google, and Intel have all have substantial quantum computing efforts
- Other large companies are exploring the broader spectrum of Quantum Technologies: *e.g. Nothrup Grumman, Lockheed Martin, Honeywell, …*
- Smaller companies are interested in either *single qubit technology* or in *supporting quantum technologies: e.g.* AOSense, Cold Quanta, QDTI, Zyvex Labs, MagiQ, Microsemi, …
- Some companies are more circumspect on their interests
- Numerous Startups (IonQ, Quantum Circuits Inc, QCWare, BraKet, PsiQuantum, … – more than 25 in the U.S. and even more abroad) – some having received significant *venture capital*

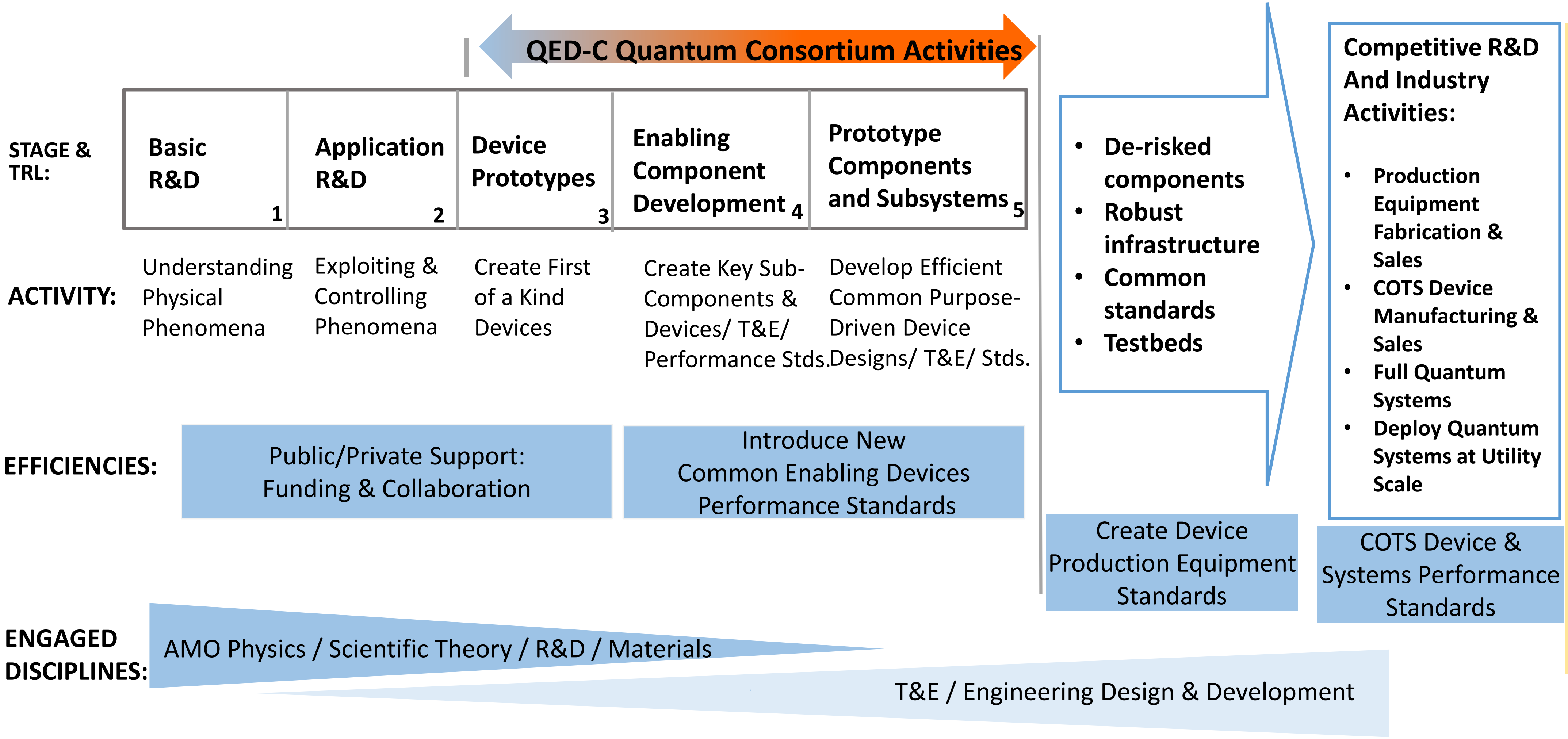
QIS Consortium Concept: Q. Engineering

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

QIS consortium purpose and objectives:

- To support enabling technology R&D and enhance the quantum ecosystem: (e.g., quantum device components, instrumentation, and performance standards)
- To facilitate industry coordination & interaction with Government agencies
- Determine workforce needs essential to the development of quantum technologies
- Provide efficient public-private sector coordination
- Identify technology solutions for filling gaps in research or infrastructure
- Highlight use cases & grand challenges to accelerate development efforts
- Foster sharing of intellectual property, efficient supply chains, technology forecasting and quantum literacy

Quantum Economic Development Consortium



QEDC is being established in partnership with SRI International under the leadership of Joe Broz, Vice President of SRI's Advanced Technology and Systems Division (ATSD)

Contact: joe.broz@sri.com

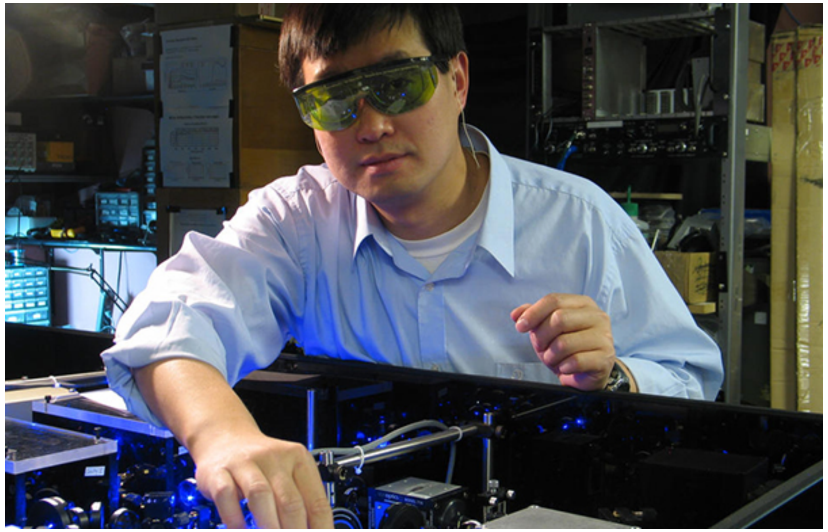
QED-C

- First meeting was held August 21, 2018 at SRI International in Menlo Park, CA
- More than Letters of Intent have been submitted to date
- Second Meeting was October 29-30, 2018 at NIST in Boulder, CO
  - Governing Board was elected: 3 large companies, 4 intermediate/small/start-up companies, and 2 government agencies
  - Technical Advisory Committee established
- 3rd Meeting on January 22-23, 2019 at CU in Boulder, CO
- 4th Meeting scheduled for April 30 - May 1 in Gaithersburg, MD
- Formal Legal structure in Fall 2019

NIST and QIS

NIST Mission

To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life



NIST Laboratories and User Facilities

Associate Director for Laboratory Programs

Standards Coordination Office
Standards Services Group
NIST Quality Manager

Special Programs Office
Forensics Standards
National Security Standards

Material Measurement Laboratory

Physical Measurement Laboratory QIS

NIST Center for Neutron Research QIS

Communication Technology Laboratory

Information Technology Laboratory QIS

Engineering Laboratory

Metrology Laboratories	National User Facilities	Technology Laboratories
Driving innovation through Measurement Science and Standards	**Providing world class, unique, cutting-edge research facilities**	**Accelerating the adoption and deployment of advanced technology solutions**

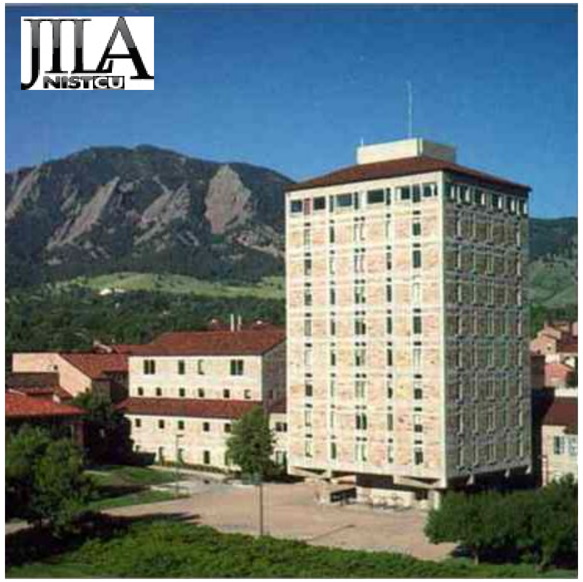
PML: Basic Stats and Facts

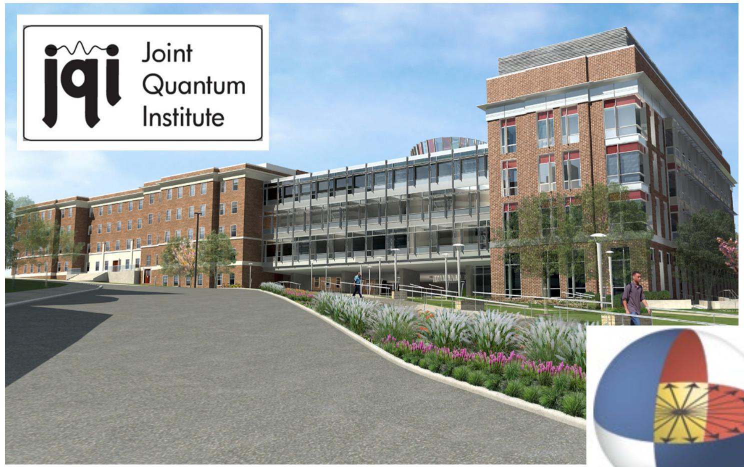
Major assets

- ~ $215 million budget [all funding sources]
- ~ 600 employees
- ~ 750 associates
- Principal activities in
  - Gaithersburg, MD
  - Boulder, CO
  - College Park, MD
  - Fort Collins, CO & Kauai, HI

Two collaborative institutes provide opportunities to:

- Attract world class scientists
- Train students and postdocs
- Transfer technology

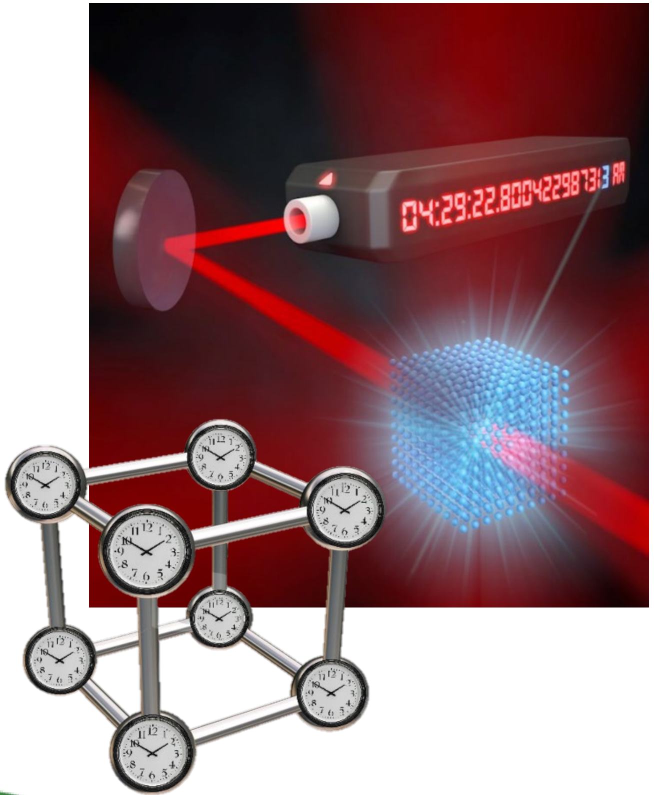


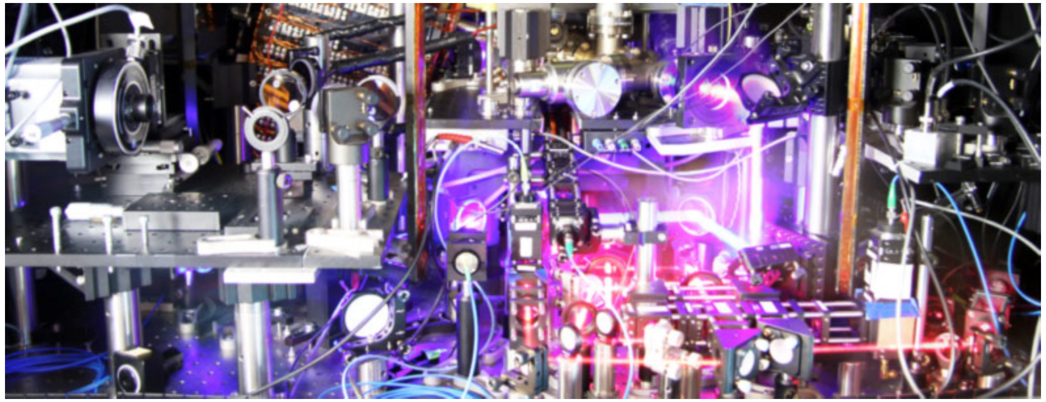


Joint Center for Quantum Information and Computer Science (QuICS) – with ITL

Quantum Degenerate Fermi Gas Atomic Clock

3D Fermi gas strontium (Sr) optical lattice clock



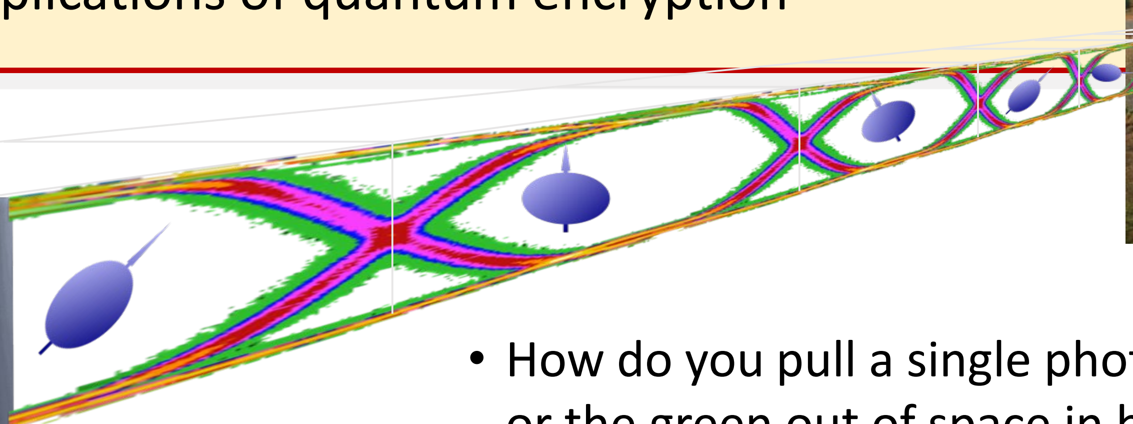


S.L. Campbell *et al., Science* **358**, 90 (2017); G.E. Marti *et al., Phys. Rev. Lett.* ***120***, 103201 (2018); Jun Ye group JILA, *unpublished.*

- First application of a quantum degenerate gas to a "practical" measurement: *A quantum-enhanced precision measurement*
  - ✓ ~1 million atoms: 100 x 100 x 100 in a 3D-optical lattice
  - ✓ Pauli exclusion: Only one atom per lattice site
  - ✓ Precision 3 x 10^{-20} in one second, on path to 10^{-22} in a few years
  - ✓ Coherence time 160 seconds and improving
- Potential laboratory for fundamental physics, including quantum gravity, dark matter detection, and long-baseline astronomical observation

Quantum Communications Effort

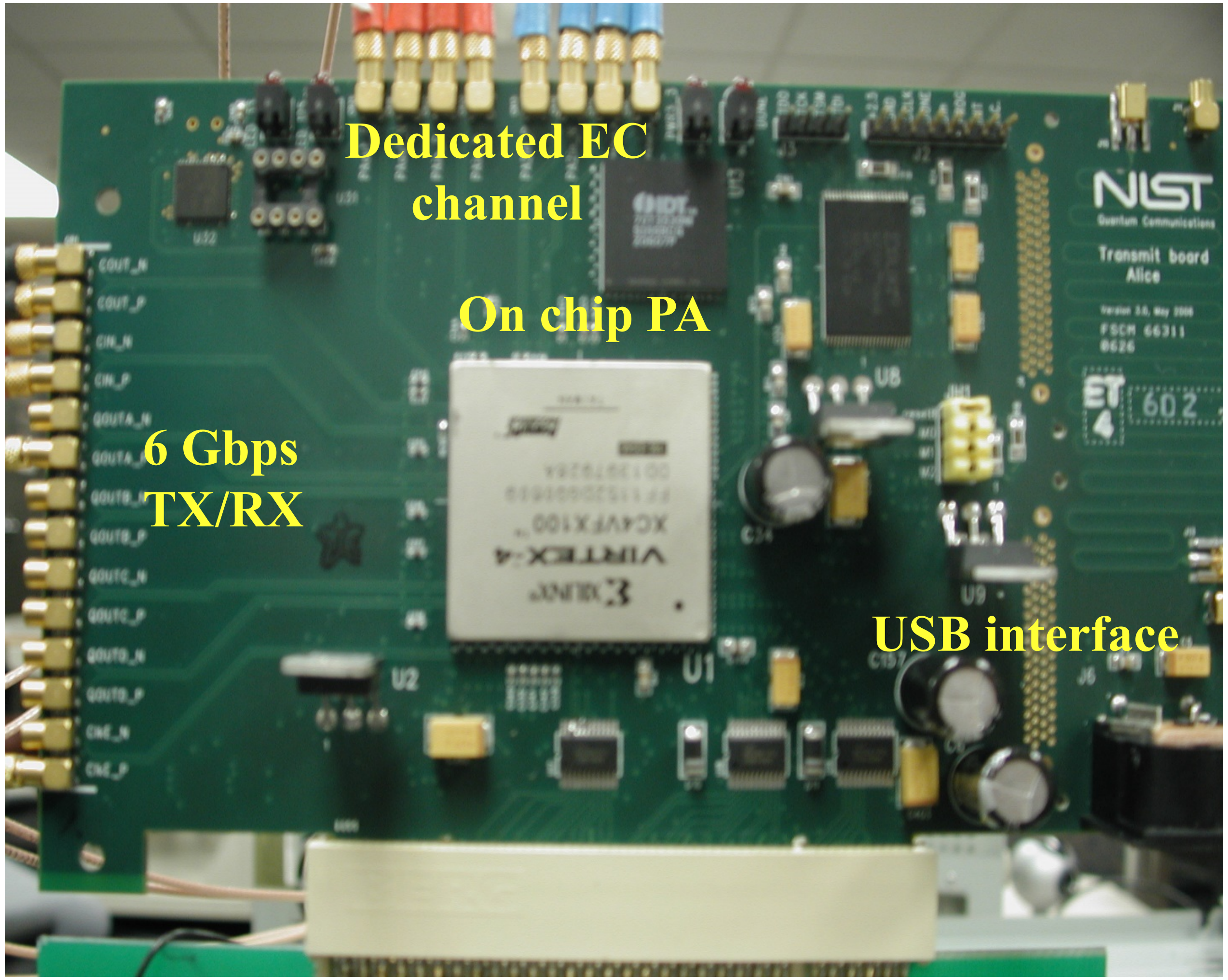
- Transmission of “*single photons*” using clock-synchronization enables up to 6 GHz rate – both free space and in fiber
- Key processing uses multi-threaded Forward Error Correction algorithm
- Demonstration of continuous one-time-pad encryption with quantum key at a data rate > 4 MB/s; ~ x100 greater than previous demonstrations
- Enables broadband applications of quantum encryption



- How do you pull a single photon in the near infrared or the green out of space in broad daylight?
- What is the physical limitation?

Josh Bienfang (PML) and Xiao Tang (ITL) – circa 2007

Faster QKD – Rev. 2.0 Board (2007)



Variable transceiver rate up to 6 GHz (166ps)

Dedicated EC channel & PA processor
➔ up to 20 Mb/s input

Memory for > 200 km

Non-PCI interface (!)
➔ Portable

Required a VIRTEX-4 (Xilinx) FPGA with 10^9 transistors. Later upgrade to the VIRTEX-5 and this is *just* QKD!

Qubit Technologies for Quantum Computing

Physical Systems for Quantum Computation

Quantum computers

T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe & J. L. O'Brien

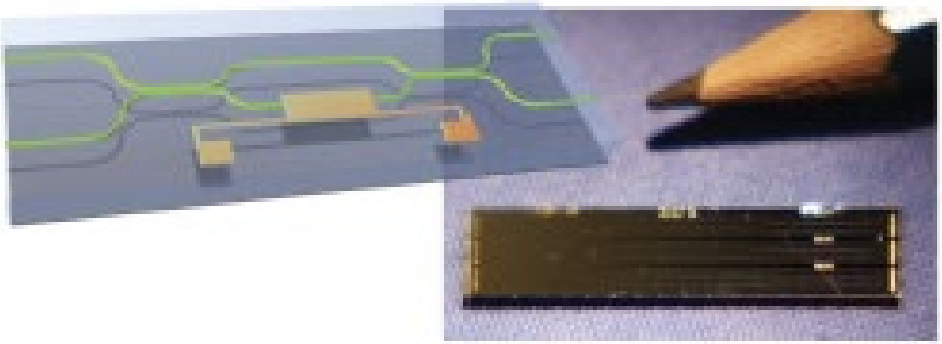
Over the past several decades, quantum information science has emerged to seek answers to the question: can we gain some advantage by storing, transmitting and processing information encoded in systems that exhibit unique quantum properties? Today it is understood that the answer is yes, and many research groups around the world are working towards the highly ambitious technological goal of building a quantum computer, which would dramatically improve computational power for particular tasks. A number of physical systems, spanning much of modern physics, are being developed for quantum computation. *However, it remains unclear which technology, if any, will ultimately prove successful.* Here we describe the latest developments for each of the leading approaches and explain the major challenges for the future.

Nature **464**, 45 2010

10 years on the article is still valid *but* Chris Monroe and Jeremy O'Brien now have venture capital funded companies

Photonic and Atomic Qubits

Figure 2 | Photonic quantum computer. A microchip containing several silica-based waveguide interferometers with thermo-optic controlled phase shifts for photonic quantum gates. Green lines show optical waveguides; yellow components are metallic contacts. Pencil tip shown for scale.



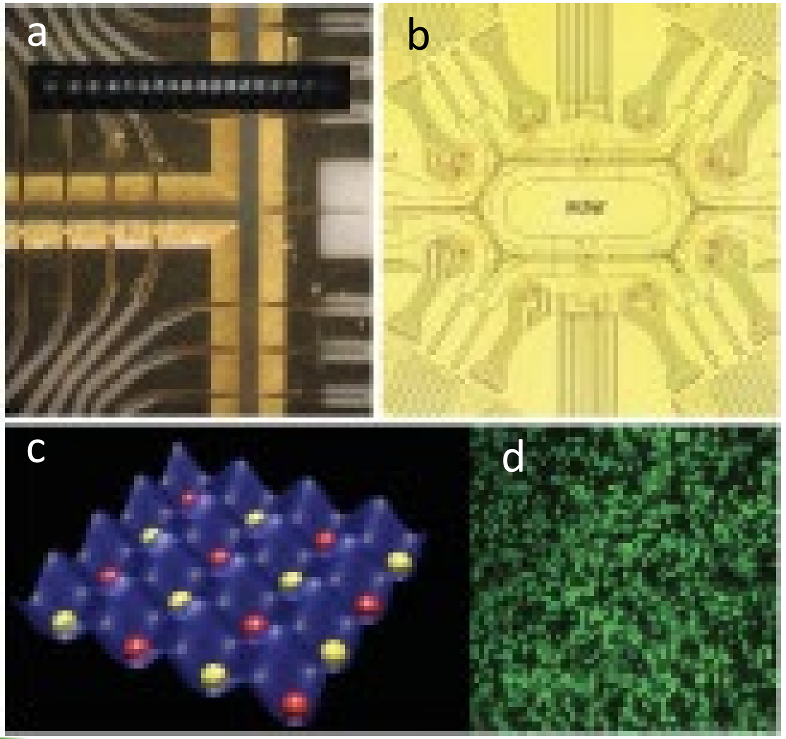


Figure 3 | Trapped atom qubits. (a) Multi-level linear ion trap chip; the inset displays a linear crystal of several $^{171}Yb^{+}$ ions fluorescing when resonant laser light is applied (the ion–ion spacing is 4 mm in the figure). (b) Surface ion trap chip with 200 zones distributed above the central hexagonal racetrack of width 2.5 mm (photograph courtesy of J. Amini and D. J. Wineland). (c) Schematic of optical lattice of cold atoms formed by multi-dimensional optical standing wave potentials (graphic courtesy of J. V. Porto). (d) Image of individual Rb atoms from a Bose condensate confined in a two-dimensional optical lattice, with atom–atom spacing of 0.64 mm (photograph courtesy of M. Greiner).

Nature **464**, 45 2010

Superconducting Qubits

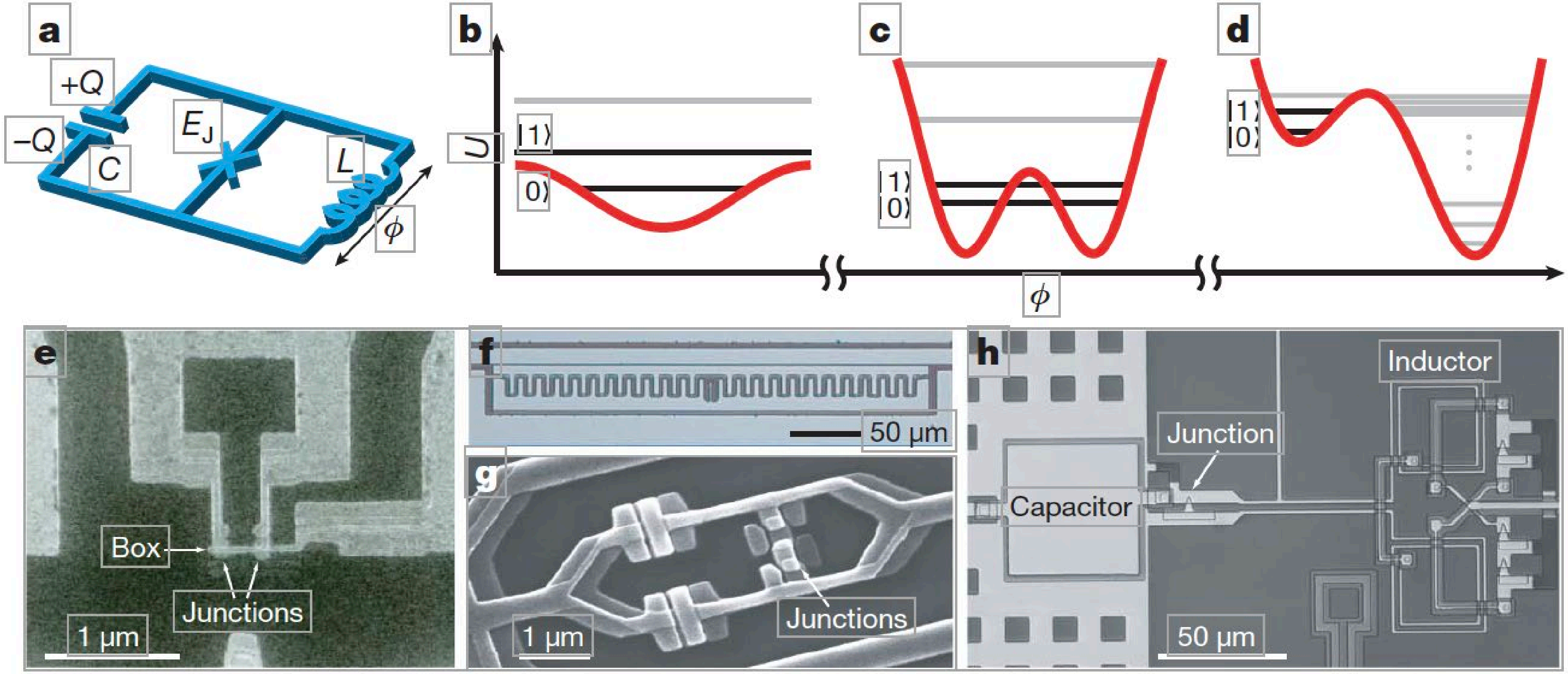


Figure 5 | Superconducting qubits. (a) Minimal circuit model of superconducting qubits. The Josephson junction is denoted by the blue 'X'. (b–d) Potential energy U($\boldsymbol{\Phi}$) (red) and qubit energy levels (black) for charge (b), flux (c), and phase qubits (d), respectively. (e–h) Micrographs of superconducting qubits. The circuits are made of Al films. The Josephson junctions consist of Al_2O_3 tunnel barriers between two layers of Al. (e) Charge qubit, or a Cooper pair box. (f) Transmon, a derivative of charge qubit with large E_J/E_C (courtesy of R. J. Schoelkopf). The Josephson junction in the middle is not visible at this scale. (g) Flux qubit (courtesy of J. E. Mooij). (h) Phase qubit (courtesy of J. M. Martinis).

Nature **464**, 45 2010

Solid State Qubits

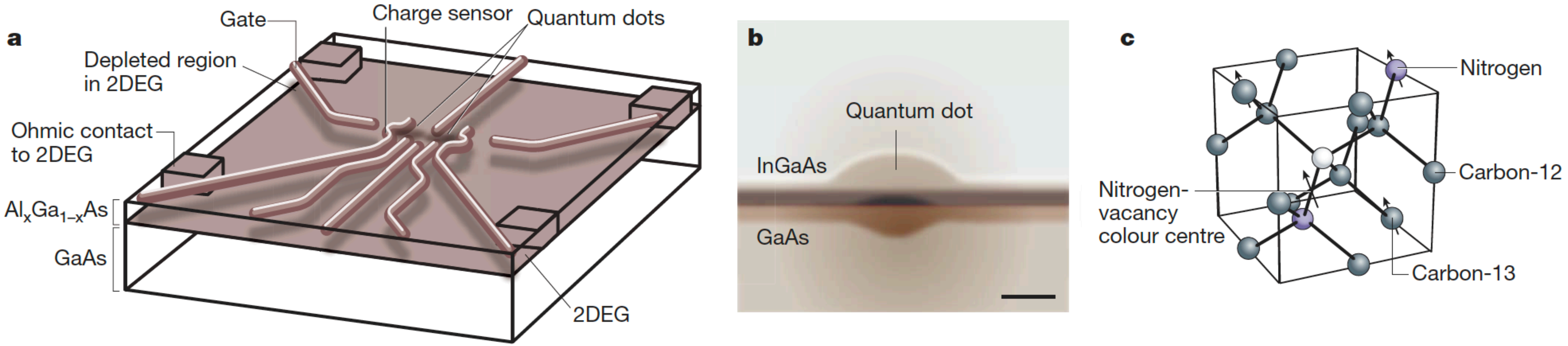


Figure 4 | Quantum dot and solid-state dopant qubits. (a) An electrostatically confined quantum dot; the structure shown is several mm across. 2DEG, two-dimensional electron gas. (b) A self-assembled quantum dot. Scale bar, ,5 nm. (c) The atomic structure of a nitrogen-vacancy centre in the diamond lattice, with lattice constant 3.6 A˚. (From Figure 1 of Nature 453, 1043–1049 (2008))

Nature **464**, 45 2010

Solid State Qubits

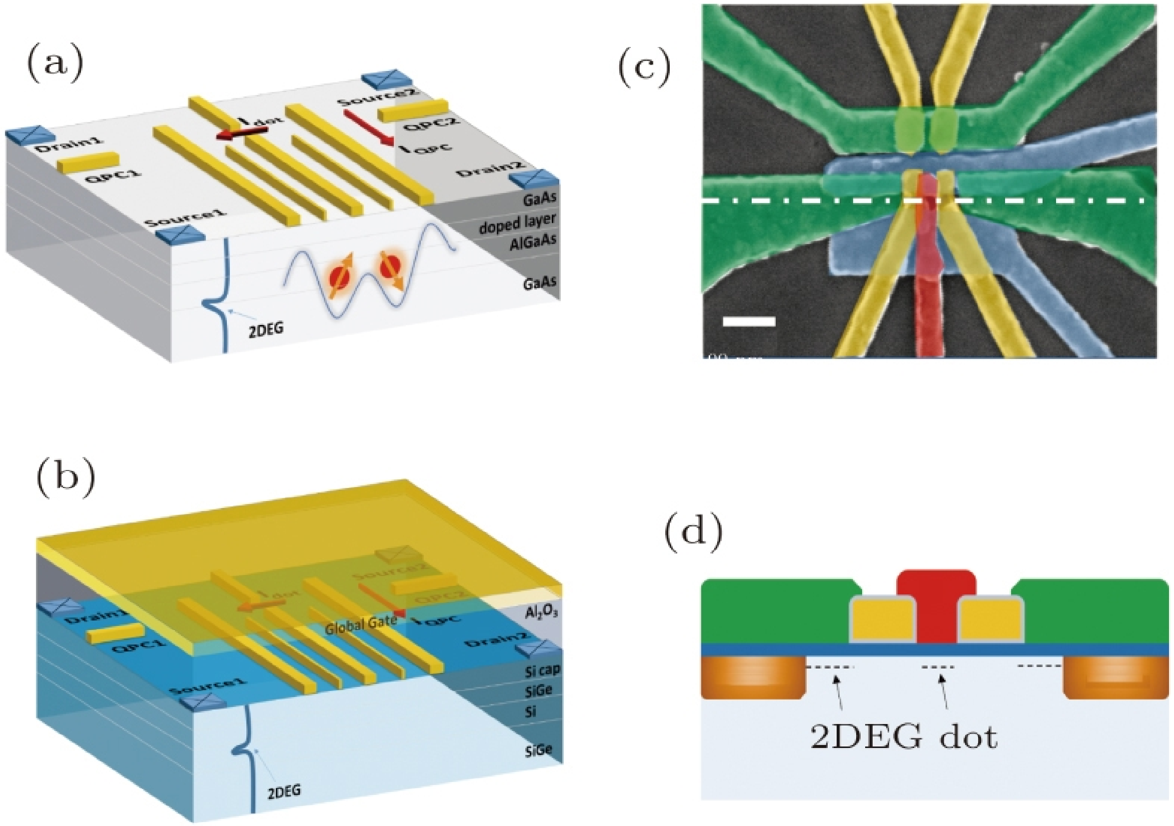


Figure 1. Device structure of the semiconductor quantum dot. Panels (a) and (b) are schematics of a double quantum dot fabricated using doped AlGaAs/GaAs heterostructure and undoped Si/SiGe herterostructure, respectively. I_{dot} is the current from source to drain through the dot, while I_{QPC} is the current from source to drain through the QPC channel. The location of 2DEG and the electrons with spin directions in the double quantum dot are also shown. (c) Scanning electron micrograph (SEM) of a CMOS quantum dot with a SET as a charge sensor, where a white dash dotted line shows position of the cross section (d). Confinement gates (blue), lead gates (green), barrier gates (orange), and plunger gates (red) are shown. (d) Cross section of a CMOS quantum dot, dotted lines denote where 2DEG and a quantum dot form.

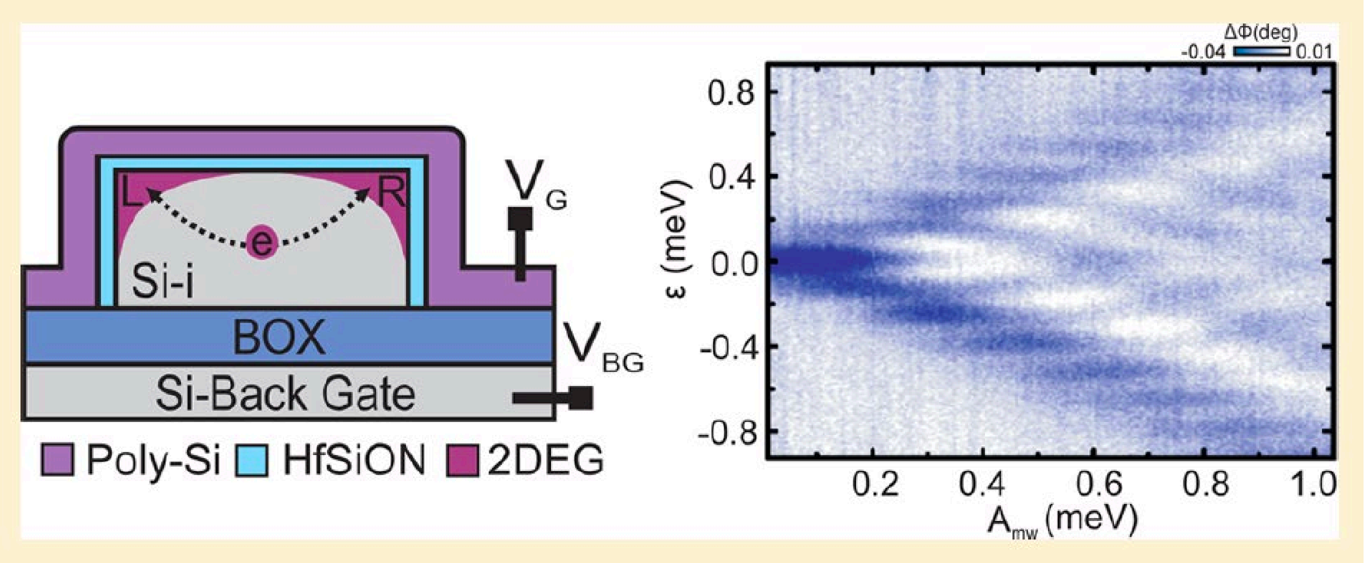
Xin Zhang *et al. Chinese Phys. B* **27** 020305 (2018)

Accidental Solid State Qubit?

Gate-Sensing Coherent Charge Oscillations in a Silicon Field-Effect Transistor

M. Fernando Gonzalez-Zalba, Sergey N. Shevchenko, Sylvain Barraud, J. Robert Johansson,
Andrew J. Ferguson, Franco Nori, and Andreas C. Betz

Quantum mechanical effects induced by the miniaturization of complementary metal-oxide-semiconductor (CMOS) technology hamper the performance and scalability prospects of field-effect transistors. **However, those quantum effects, such as tunneling and coherence, can be harnessed to use existing CMOS technology for quantum information processing**. Here, we report the observation of coherent charge oscillations in a double quantum dot formed in a silicon nanowire transistor detected via its dispersive interaction with a radio frequency resonant circuit coupled via the gate.



Nano Letters **16**, 1614 (2016)

Other Qubits and Issues

- Topological qubits
- Doped graphene, carbon nanotubes, or fullerenes
- Rare earth ions in crystalline structures

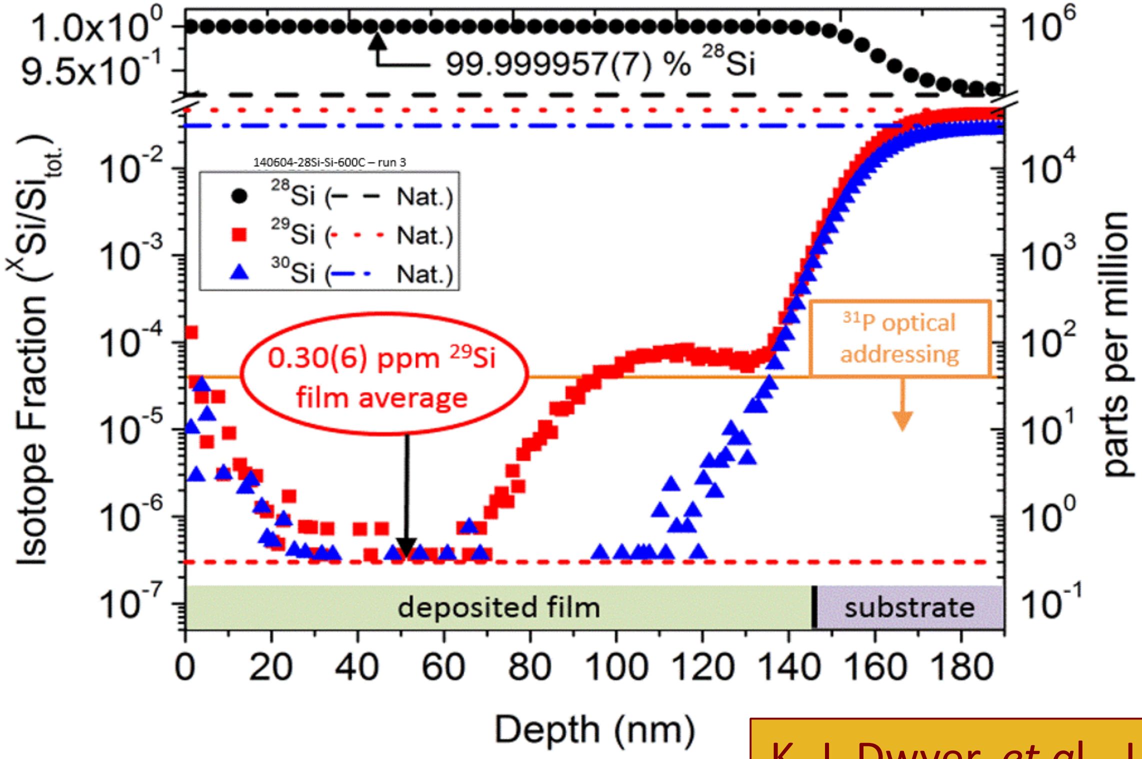
Photonic qubits can be used in *so-called* cluster state quantum computation, which is a measurement based, fast feed forward computation

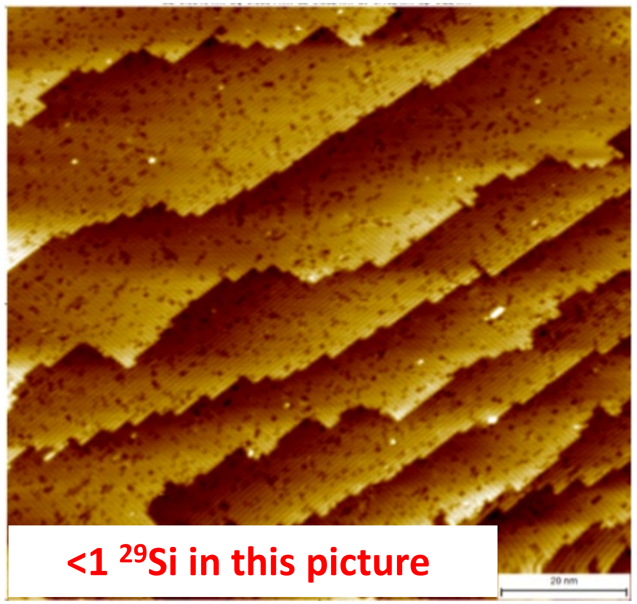
NIST has qubit activities in atoms, ions, photons, superconducting, and gated Si and GaAs dots and P-doped Si

Enriched ^{28}Si for 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.





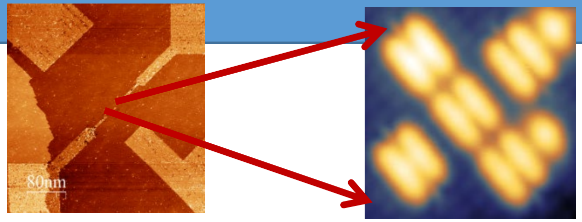
Enriched silicon has been shown to dramatically extend coherence (T2) times and also reduce optical linewidths. We are producing the most highly enriched silicon known, allowing the technical limits of these benefits to be tested while providing an enabling source for ongoing Si QIS qubit efforts based on these benefits.

K. J. Dwyer, *et al*., J. Phys. D: Appl. Phys. **47**, 345105 (2014)

Single Atom Devices

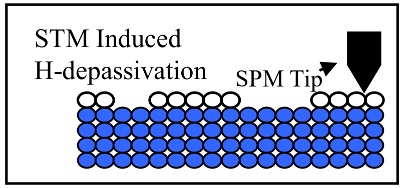
We are building the foundation to make, measure, and model atomic devices for future classical and quantum computing. Developing the metrology to characterize few atom structures using atomically resolved scanning tunneling spectroscopy, aberration corrected TEM, atom probe tomography, and transport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

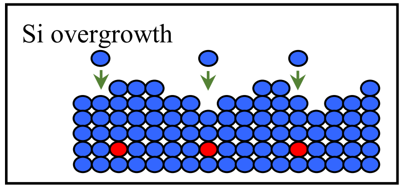
- A scalable solid state architecture for silicon QI
  - Control the quantum state of an individual electron
  - Materials that preserve the quantum state of an electron
- Atom technology for ultimately scaled Si electronics
  - Single and few atom transistors
  - Atomically abrupt tunnel junctions
- New materials with designer electronic and optical properties

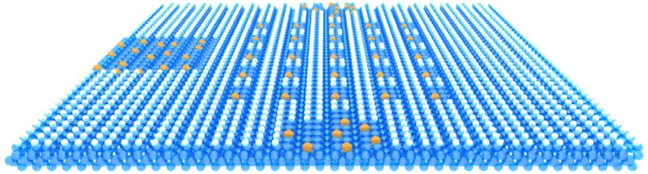


Gated Quantum Dot Device

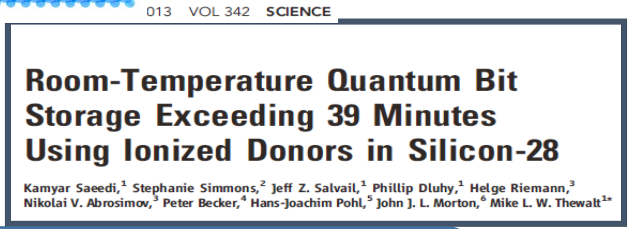
Atomic scale patterning







Engineering atomically precise materials


013 VOL 342 SCIENCE

Room-Temperature Quantum Bit Storage Exceeding 39 Minutes Using Ionized Donors in Silicon-28

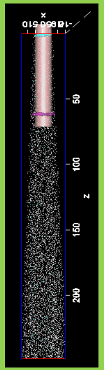
Kamyar Saeedi,[1] Stephanie Simmons,[2] Jeff Z. Salvail,[1] Phillip Dluhy,[1] Helge Riemann,[3] Nikolai V. Abrosimov,[3] Peter Becker,[4] Hans-Joachim Pohl,[5] John J. L. Morton,[6] Mike L. W. Thewalt[1*]

We are developing fundamentally new measurements of local electronic states, energy spectra, and electron coherence as well as methods to measure with atomic precision <u>as devices are made.</u>

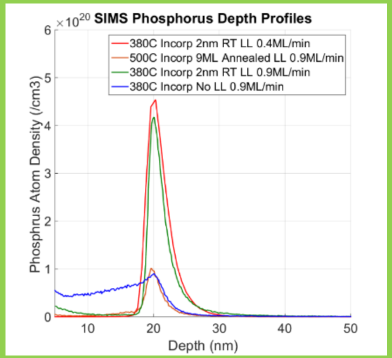
Metrology for Single Atom Device Fabrication

- Characterization of phosphorus doped delta layers – aberration corrected TEM, atom probe, and transport to develop SIMS model
- Use scanning capacitance to relocate near atomic scale devices for ebeam patterning of via contacts to buried devices.
- Atomic resolution spectroscopy to study electronic properties of as-fabricated atomic devices.

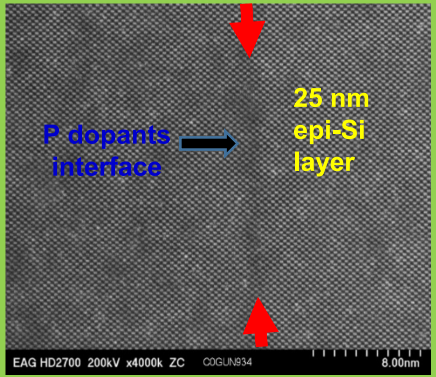
P dopants interface



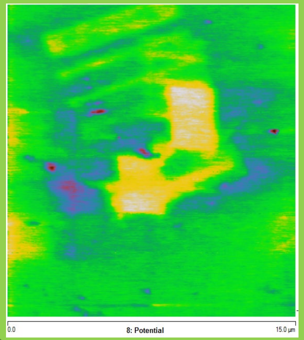
Atom probe tomography of delta layer sample with near 3-D atomic resolution.

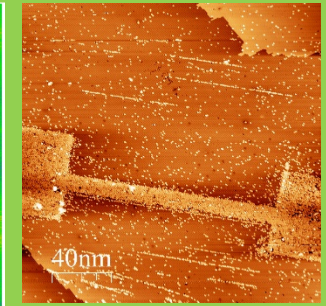


Developed SIMS deconvolution/segregation model to extend SIMS resolution to the atomic regime

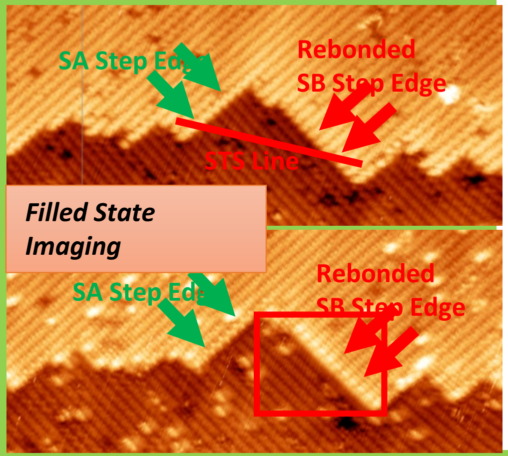


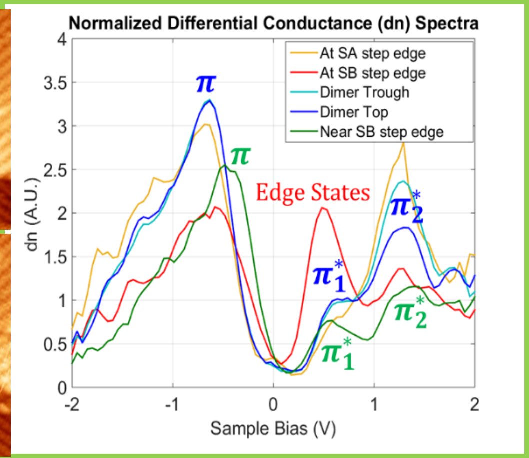
Aberration corrected STEM image





STM image of a 12 nm patterned line on the right. Left image is a Peak Force Kelvin data of the buried nanometer scale structure before ebeam vias are writen.





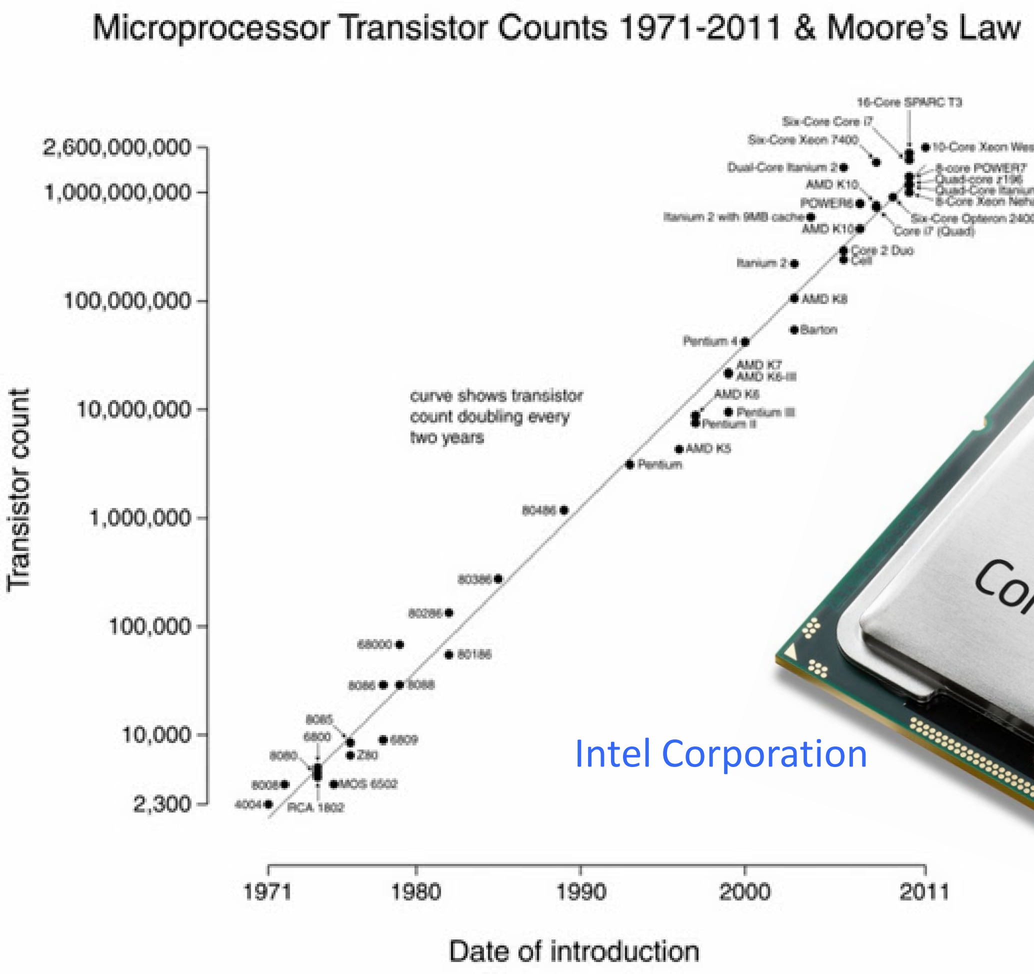
Atomic resolution spectroscopy of electronic structure

X.Wang, P. Namboodiri, K, Li, et al., Sept. 2016, Phys. Rev. B

Operating beyond the limits of current transmission electron microscopy and atom probe! STM, APT, TEM, SIMS, and electrical characterization are combined to characterize individual atomic configurations.

From Physical to Logical Qubits and the need for Transistors

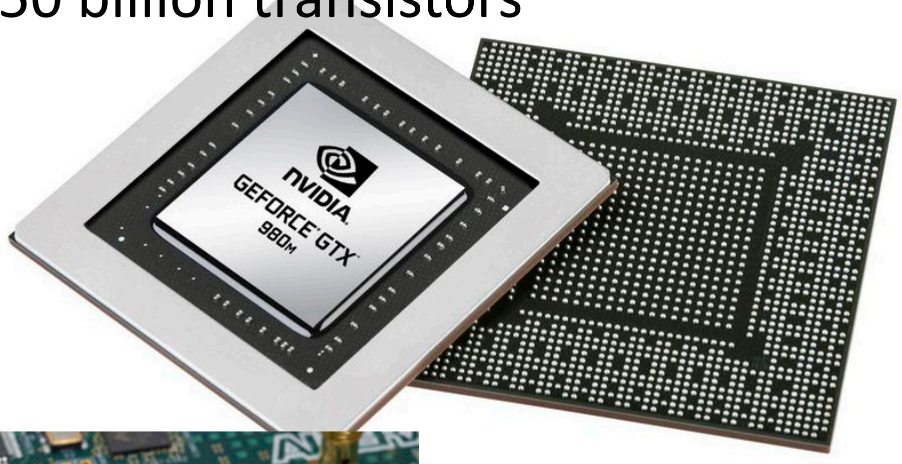
Current Transistors Count



https://en.wikipedia.org/wiki/Transistor_count

- Modern IC chip: ~10 billion transistors
- GPU: ~20 billion transistors
- FPGA: ~50 billion transistors

Intel Corporation



NVidia Corporation

Altera Corporation

Qubits Needed

- General purpose quantum computation requires a *logical qubit* since it is impossible to error correct a *physical qubit* – the no-cloning theorem
- Error correction of a *logical qubit* is achieved by measuring the error syndrome and thus learn nothing about the *encoded state of the qubit*
- A logical qubit will require 10 (very optimistic) to 1000 physical qubits – assuming in the latter case multiple levels of encoding
- Typical computation (factoring of 1048 RSA or a reasonable quantum chemistry calculation) will require 10,000 *logical qubits*
- Overhead for movement, swapping, and ancilla is another factor of 10

Final estimate 1000 x 10000 x 10 = 10^8 a 100 Mega-qubits

Transistors needed for Memory and Control

- Estimate is about 2 kbits of memory per qubit
  - 8 bits of resolution
  - 16 samples per gate or instruction
  - 16 instructions per qubit → 8 x 16 x 16 = 2kbits → 1.2 x 10^4 transistors assuming ultra low power CMOS base DRAM
- Roughly a similar number of transistors for the Arbitrary Wave Generator (AWG) needed to control the qubits
- Thus 10^4 – 10^5 transistors per qubit
- Or a total of 10^{12} – 10^{13} transistors to run my quantum computer!

Of course someone out there may be very clever

Key Take Away Points

- Need to build a Quantum Information Science (QIS) ecosystem just as there exists an ecosystem for semiconductors and nanoelectronics
  - Various technologies will be required
  - Some quantum 1.0, some quantum 2.0, some infrastructure
- Natural evolution of semiconductor or nanoelectronics may lead to qubits for quantum computing – *but also may not*
- Finally and *most significantly* the most complex semiconductor or nanoelectronics control system ever designed will be the one built to control the *general purpose* quantum computer
  - Will need to be fast
  - Will have to be very low power → nW per transistor
  - May need to operate at very low T and/or in vacuum

Risks and Issues

- There is much hype and the *current rapid growth* especially in quantum computing will likely stall at some point
- Pipeline of knowledgeable people is beginning to stress the field
- OEM in U.S. are only beginning to engage → QEDC should help
- Too much focus on Quantum Computing
- A general purpose quantum computer requires:
  - Logical Qubits (10-1000 qubits per every physical qubit) and thus ~10^8 qubits
  - Much infrastructure including dilution refrigerators, quantum transduction, stable lasers, …
- And whatever the winning technology, one needs 10^{12} – 10^{13} transistors!

Questions?

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