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Engineering materials for quantum information science

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Institute for Molecular Engineering, University of Chicago

Argonne National Laboratory

- research developments
- opportunities for science and technology
- challenges and needs

telecom
energy
electronics

medicine
transportation
defense

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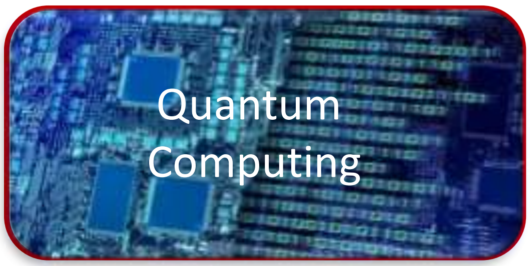
Quantum information science

All physical systems are governed by the laws of quantum mechanics

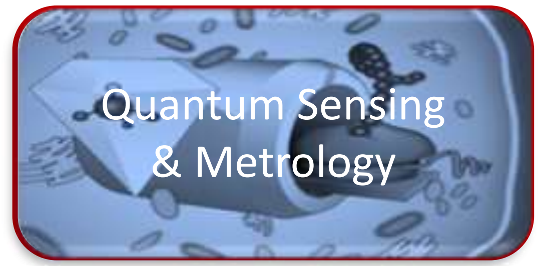
Quantum information processing

- creating, controlling, and communicating information at the quantum level
- using atoms, ions, photons, solid state systems



Solve problems intractable to classical computers, simulating large physical systems, factoring

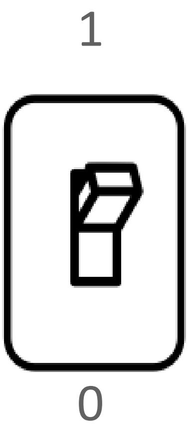
Distribute quantum states between distant parties for ultra-secure cryptography



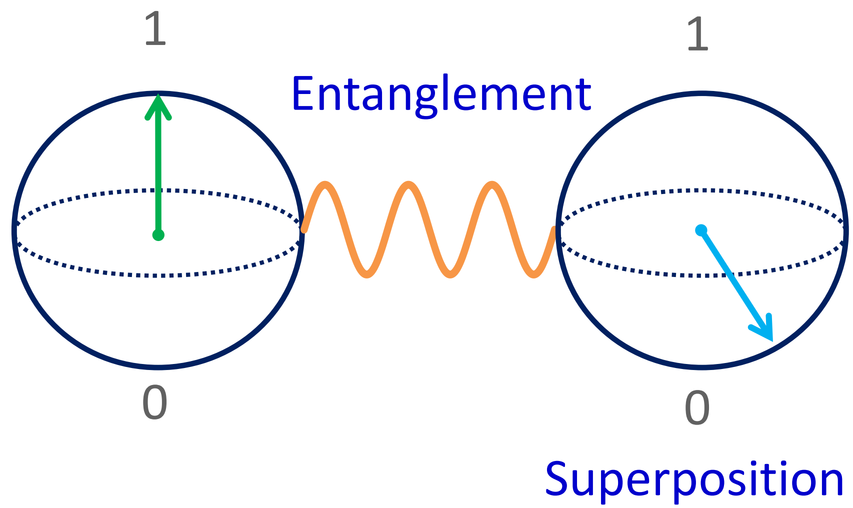
Sense physical degrees of freedom with high precision down to nanometer scales

Counterintuitive effects: “*quantum weirdness*”

Classic bit:
e.g. electron charge



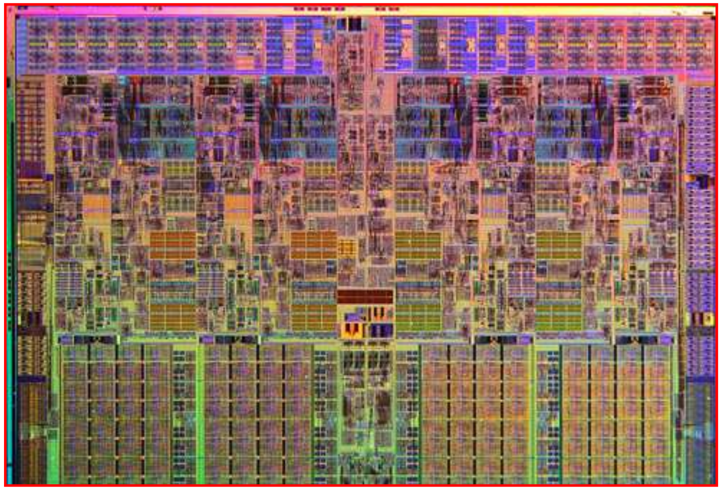
Quantum bit (qubit):
e.g. electron spin



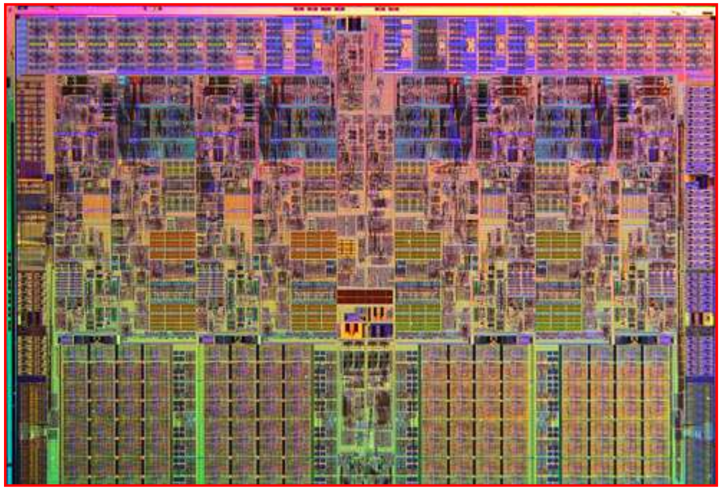
Quantum bits rewrite the rules and can outperform classical bits for specialized tasks:

- algorithms for searches and factoring prime numbers
- secure communication and encryption
- simulating complex systems

Power of classical scaling



Intel Core-I7 CPU
- Four cores
- 700 million transistors



Intel Core-I7 CPU
- Four cores
- 700 million transistors

DOUBLING THE NUMBER OF TRANSISTORS DOUBLES THE COMPUTATION POWER (ROUGHLY)

Power of quantum scaling

Perspective

Quantum computer size	Classical memory sites to record state of device	Simulate dynamics: exponentiate
50 qubits	**$2^{50} = 10^{15}$ sites**	**10^{15} by 10^{15} matrices**
100 qubits	~10^{30} sites	10^{30} by 10^{30} matrices

Quantum computer "Mark I"

- 10,000 qubits (equiv. to a transistor)
- Maximum interconnectivity

Adding ONE qubit DOUBLES the power of a quantum computer

DOUBLING THE NUMBER OF QUBITS CREATES A COMPUTER $2^{10,000}$ AS POWERFUL (ROUGHLY)

Physical platforms

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	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Science **354**, 1091 (2016)

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Material: maintain "quantumness"

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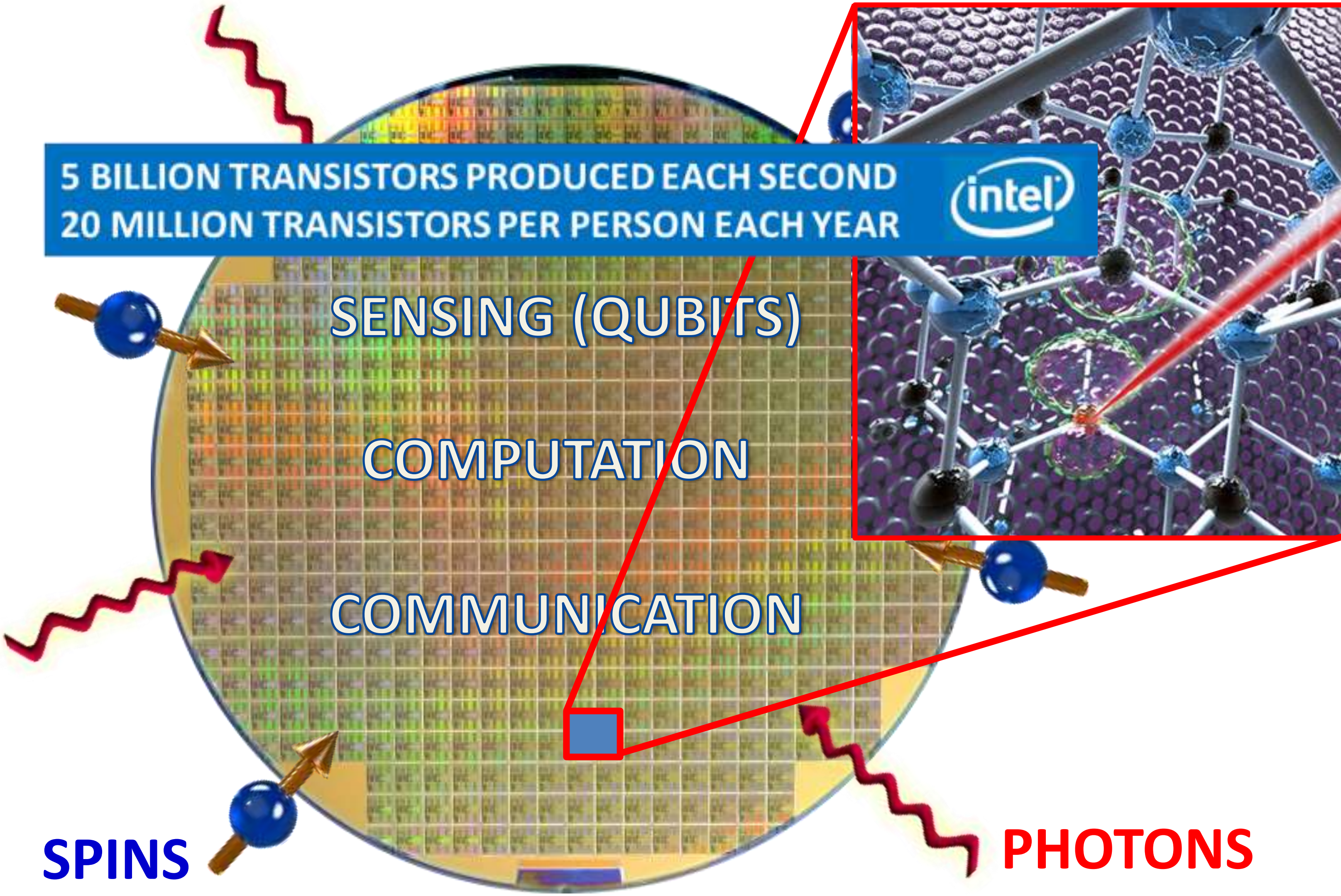
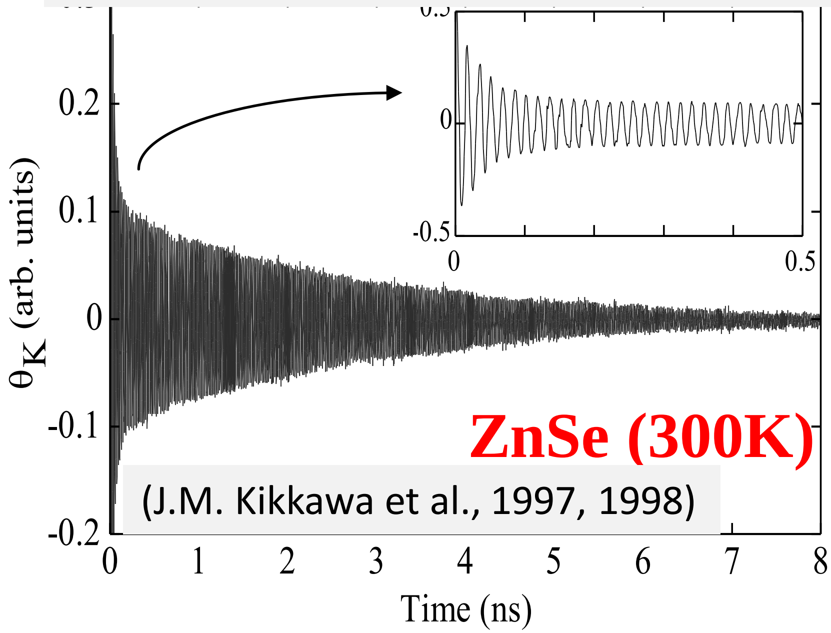


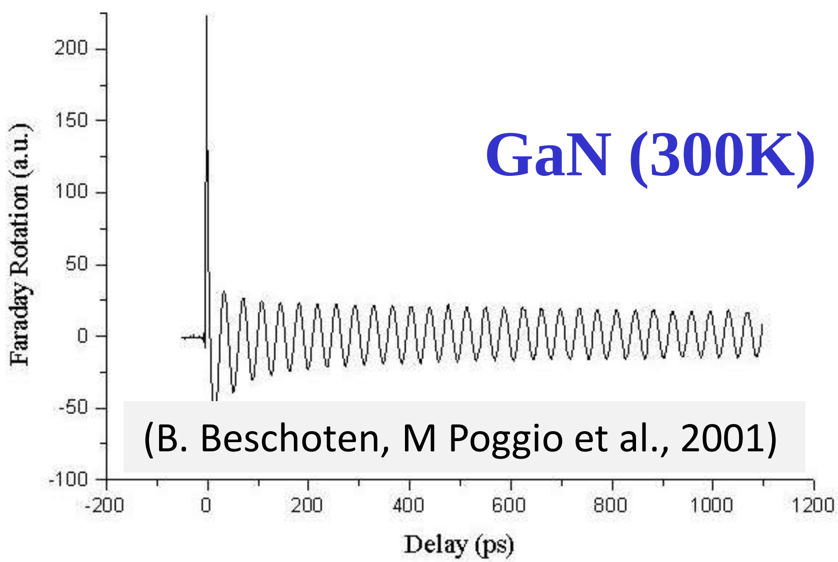
SEMICONDUCTORS

Ensemble electron spin coherence in semiconductors

Time-evolution of Faraday rotation

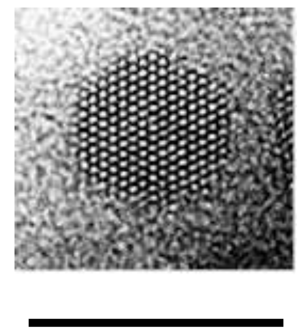


(J.M. Kikkawa et al., 1997, 1998)



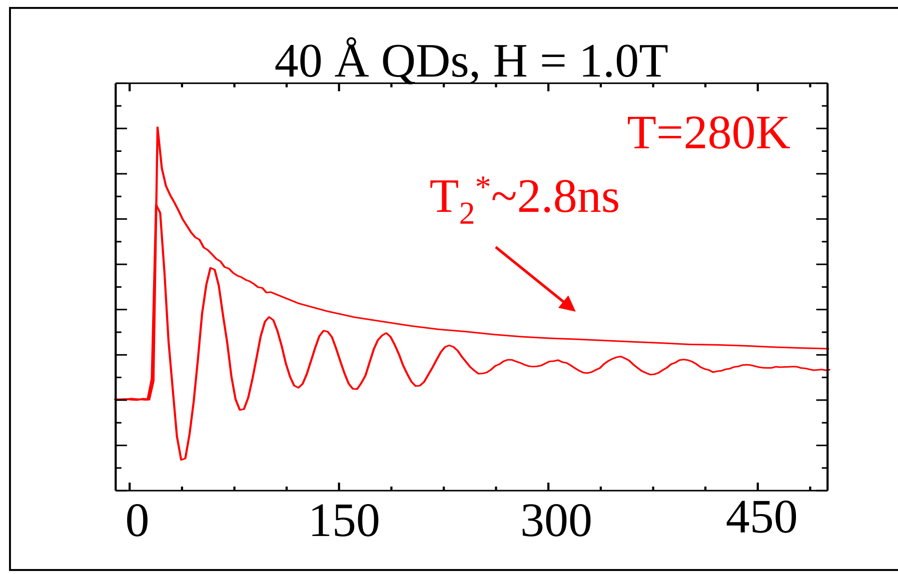
(B. Beschoten, M Poggio et al., 2001)

Quantum dots



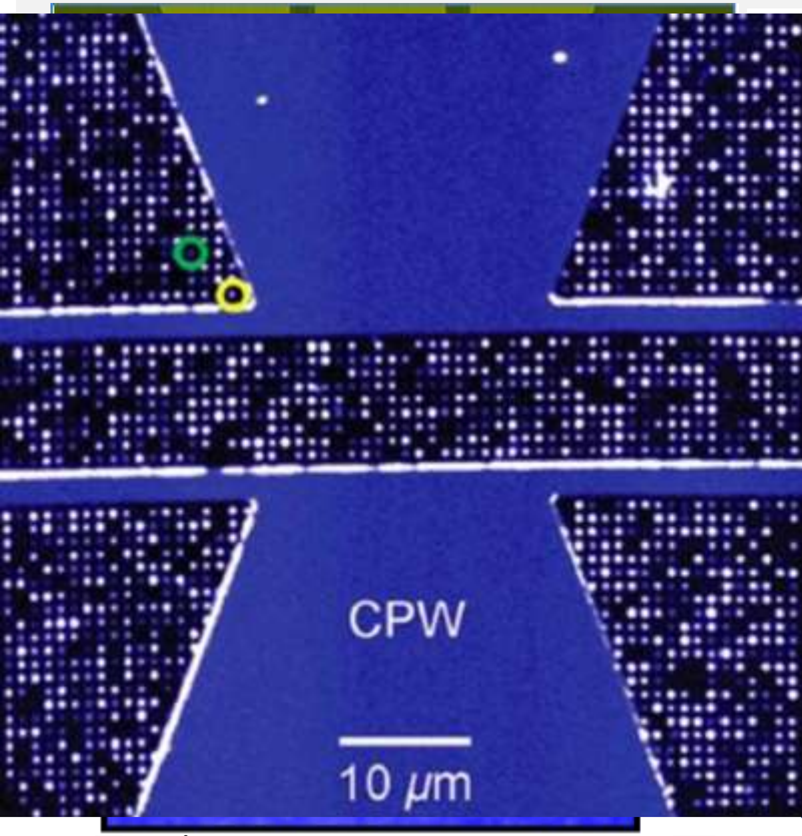
TEM of a CdSe QD

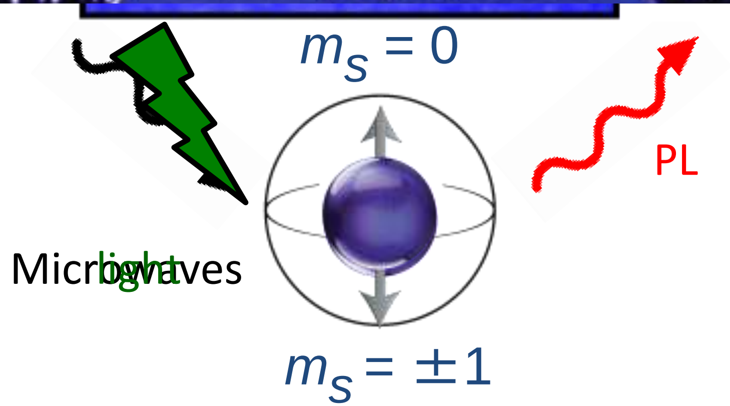
- chemically-synthesized
- single crystal QD
- size distribution (5%)
- size control: 2-10 nm
- surface flexibility: cap
  - ligand chemistry
  - inorganic capping

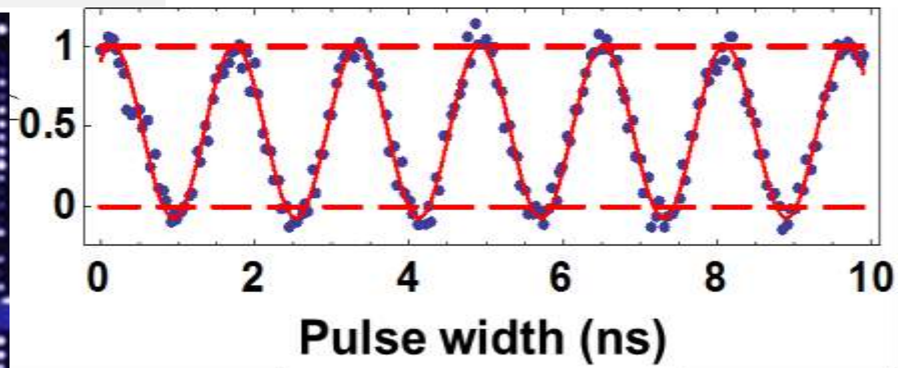


(J.A. Gupta *et al.*, *PRB* 1999, 2001, 2002)

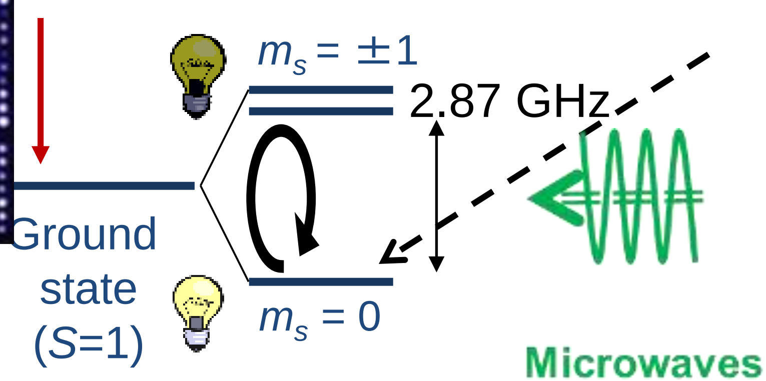
Single spins in semiconductors: embracing defects







Optically-detected magnetic resonance
GHz room temperature operation



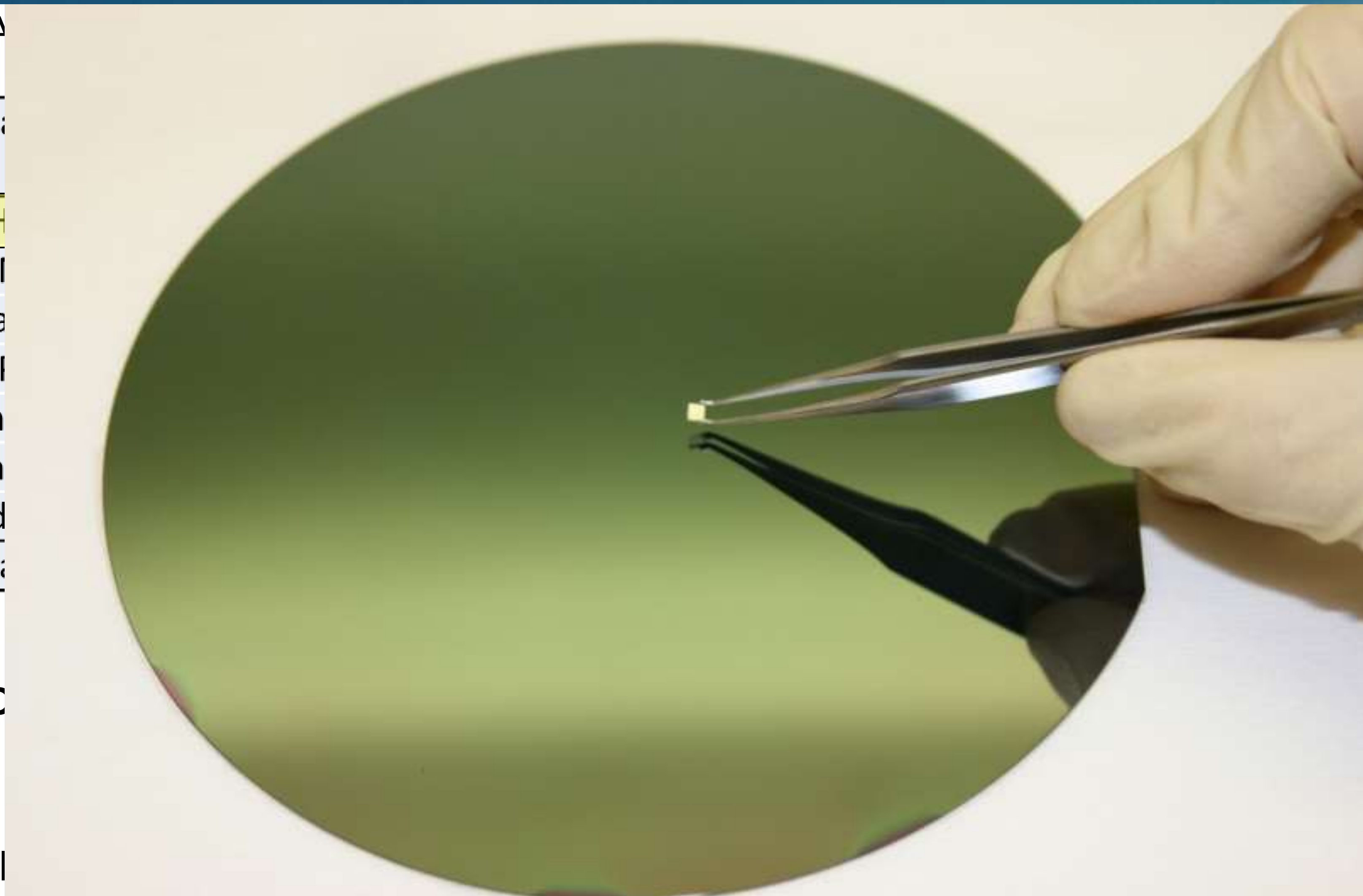
Science **326**, 1520 (2009)

- Optical spin polarization and readout via photoluminescence
- Microwave spin control… room temperature

Computation-driven exploration: new materials

❑ A

M
4H
Al
Ga
Al
Zn
Zn
Cd
Di



❑ **D**

(coll

Galli group, U Chicago)

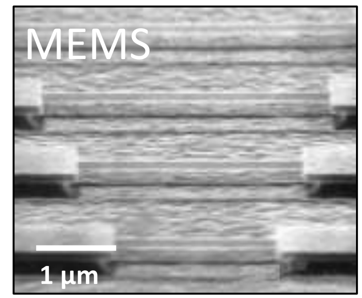
Proc. Natl. Acad. Sci. **107**, 8513 (2010)
Nat. Comm. **7**, 12935 (2016)

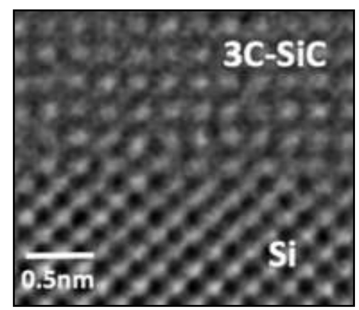
Silicon carbide (SiC) as a quantum host

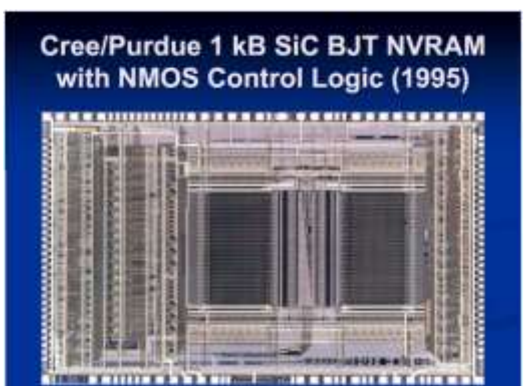
Flexible material properties
- over 250 crystalline forms (polytypes)
- variable properties (e.g. band gap)
- spin qubits in most common polytypes*

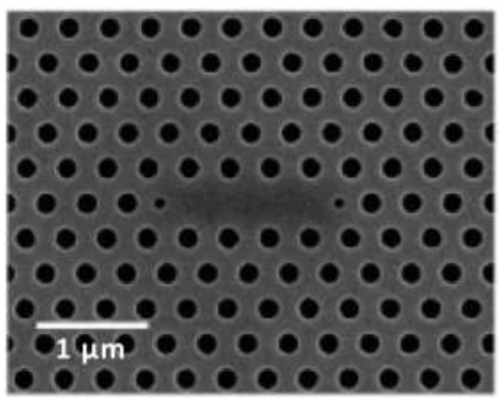
Device friendly
- SI/p/n-type wafers for purchase
- commercial high-power electronics
- commercial optoelectronics
- high quality MEMS/NEMS

Heteroepitaxy
- substrate for GaN, graphene, SiC polytypes
- can be grown epitaxially on Si





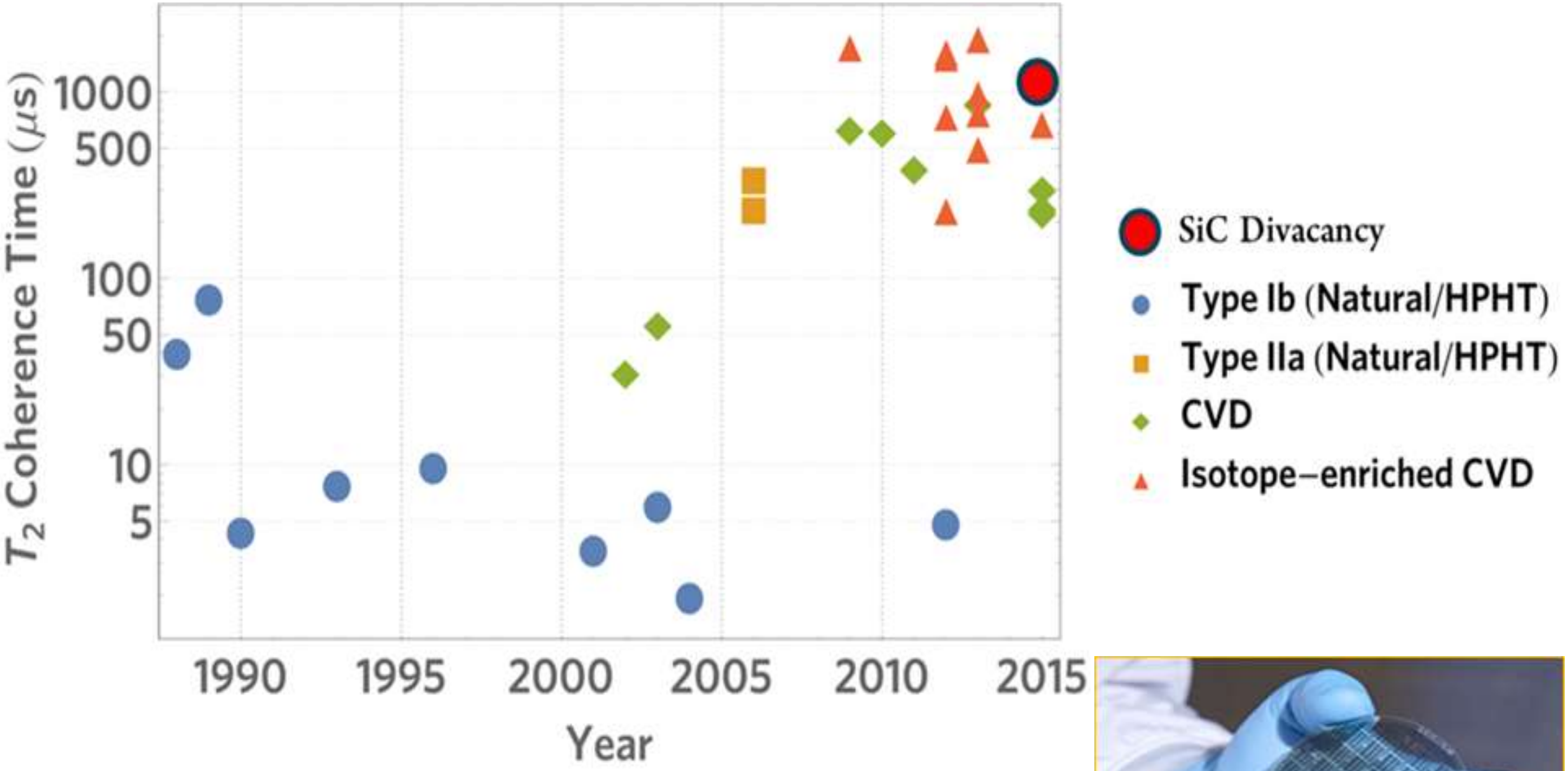


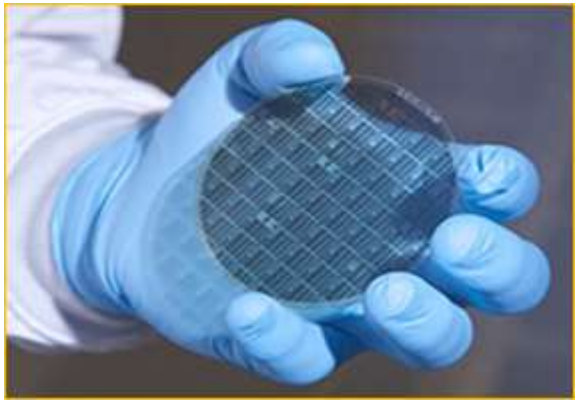


Appl. Phys. Lett. (2014)

Nat. Com.* **4, 1819 (2013)

Detection of a single spin in a SiC wafer

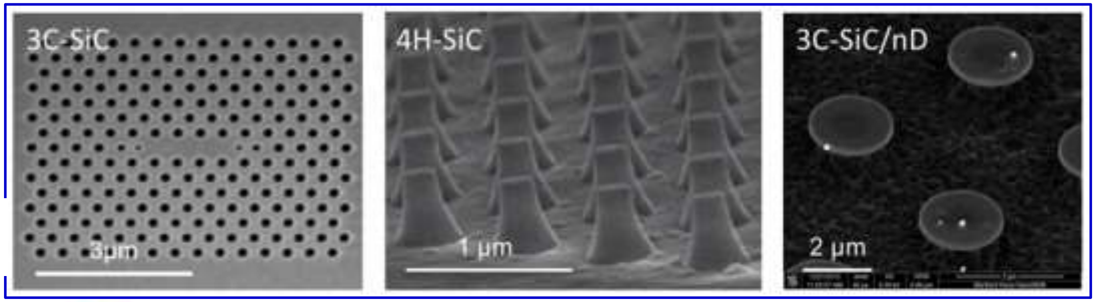


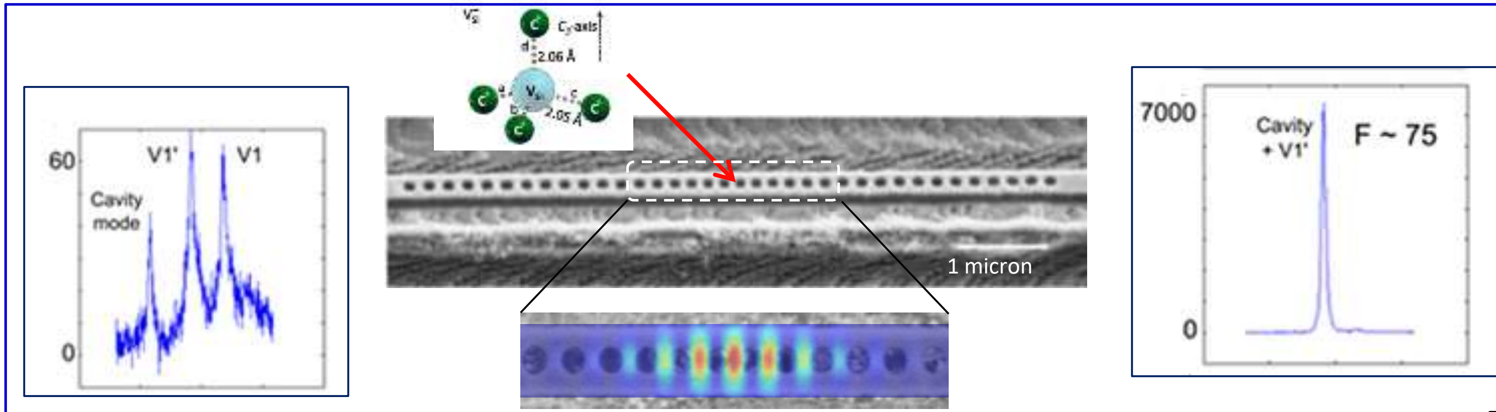


Phys. Rev. X **7**, 021046 (2017)

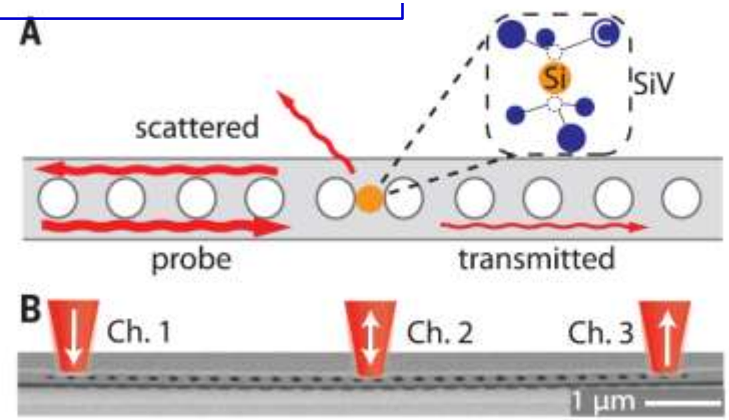
Quantum coherent interfaces: light-matter control

J. Vuckovic, Stanford





PNAS **114**, 4060 (2017)



Integrated quantum nanophotonics

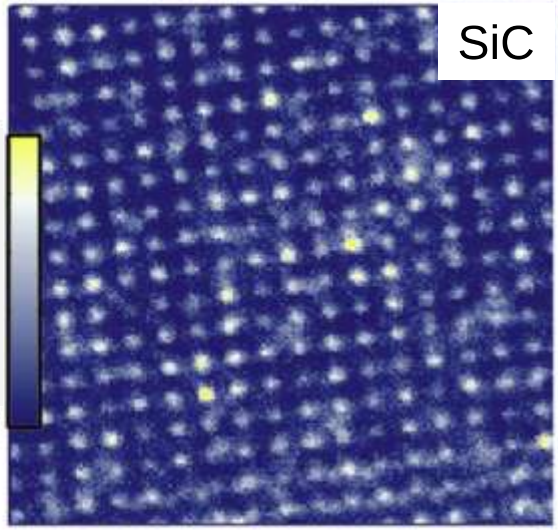
- single photon quantum optical switches
- platform for controlled entanglement
- controlling light-matter interactions

Science **354**, 847 (2016)

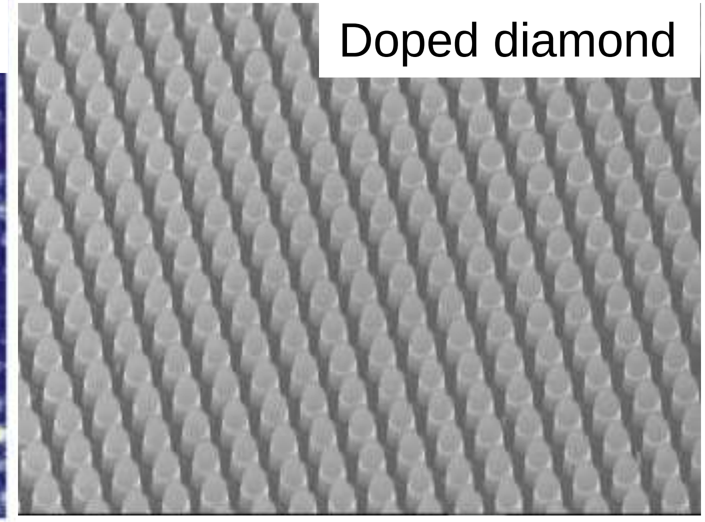
Rapid developments in materials engineering

Engineering and patterning spins

- wafer-scale implantation
- lithography



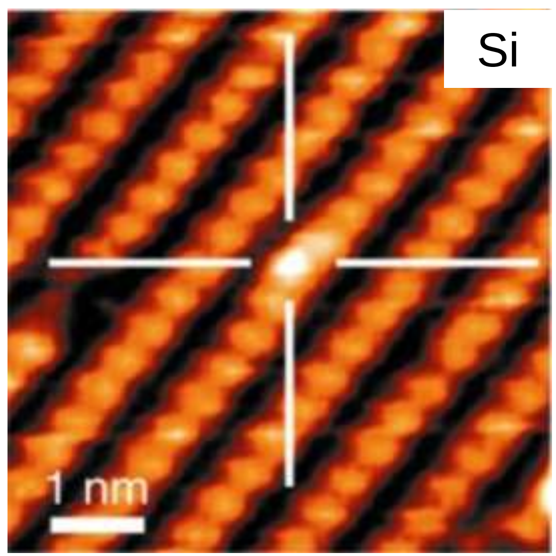
Nature Comm. **4**, 1819 (2013)



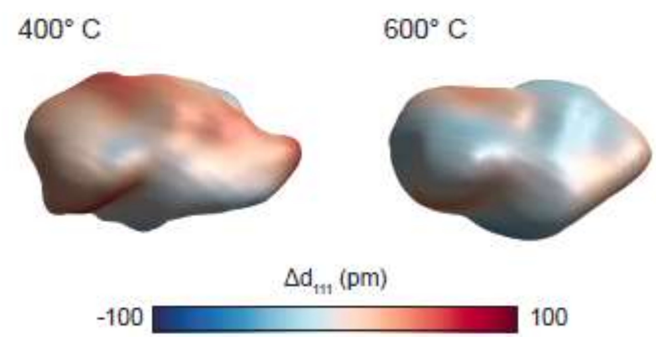
Nanoletters **14**, 4959 (2014)

Atomic-level placement and characterization

- STM techniques
- structural imaging

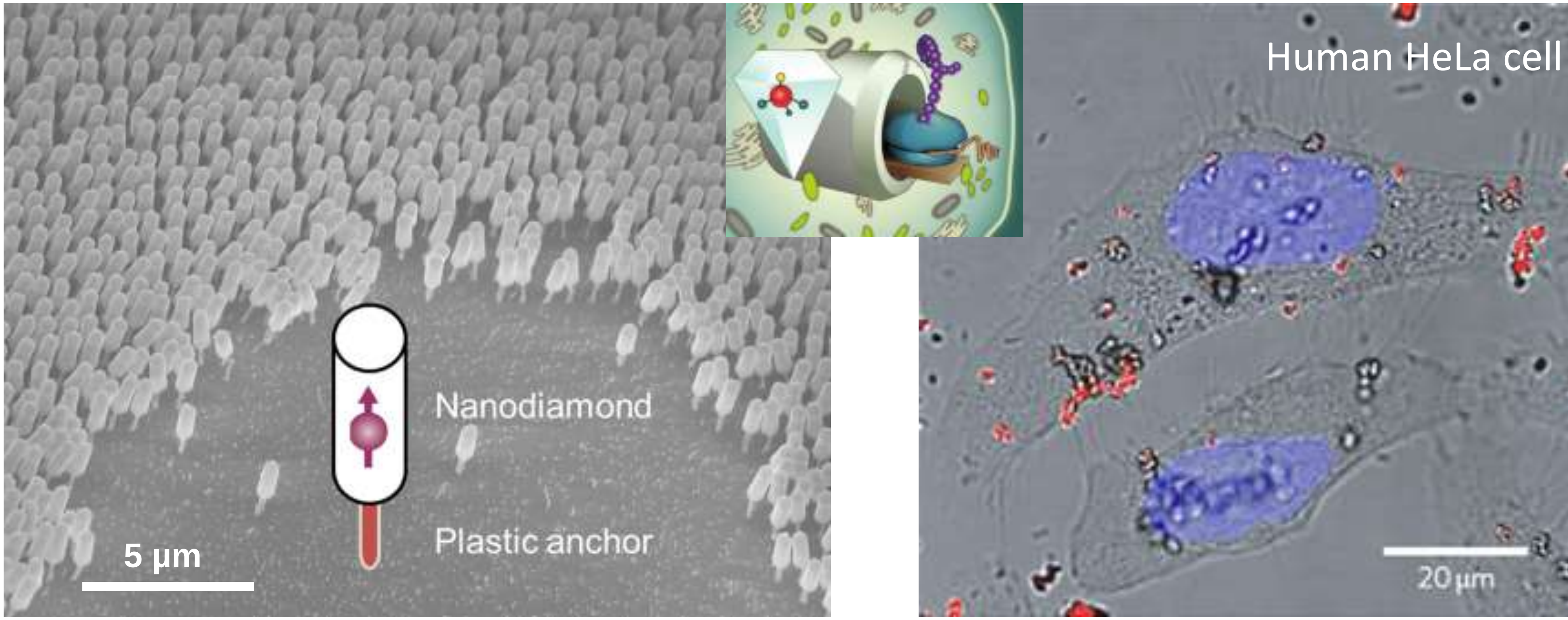


Michelle Simmons



APL Materials **5**, 026105 (2017)

Quantum states for communication and sensing



Nano Lett. **14**, 4959 (2014)

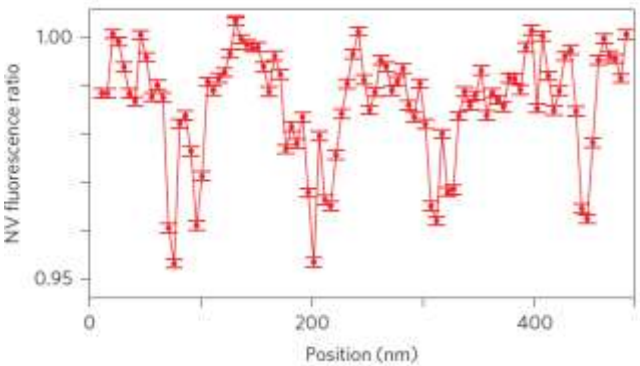
Nature Nano. **6**, 358 (2011)

- quantum sensors enable magnetic field, electric field, and temperature measurements
- cryogenic, room temperature and higher temperature operation (up to 700 K)
- biologically-inert and compatible with living cells (intracellular probes)
- high spatial resolution using nanoparticles, tunable size, high sensitivity

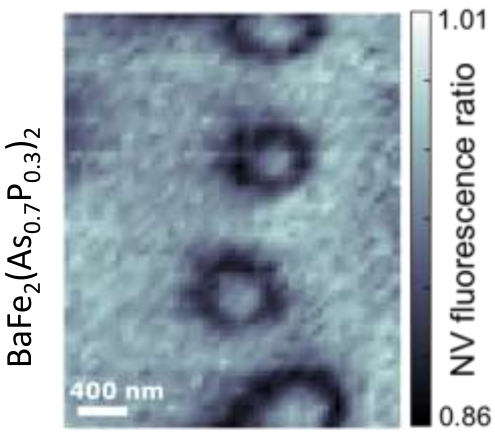
Every qubit is also a sensor

Quantum sensing

Magnetic fields

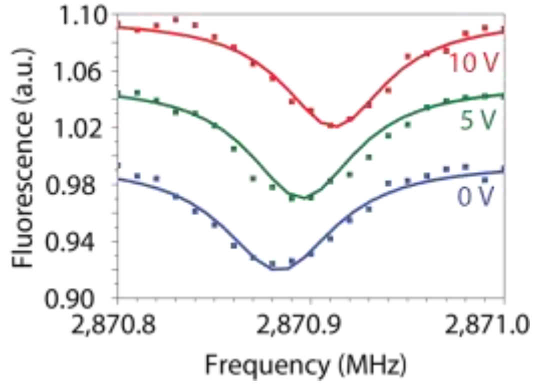


Nat. Nano. **11**, 700 (2016)

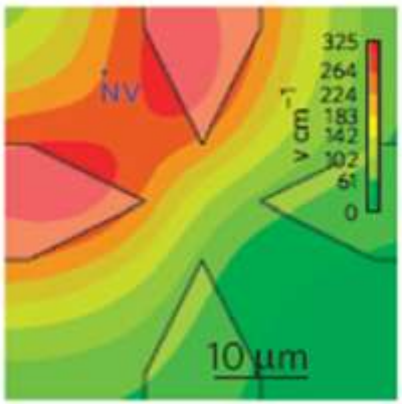


$$\eta \sim 10 \frac{\mathrm{nT}}{\sqrt{\mathrm{Hz}}}$$

Electric fields

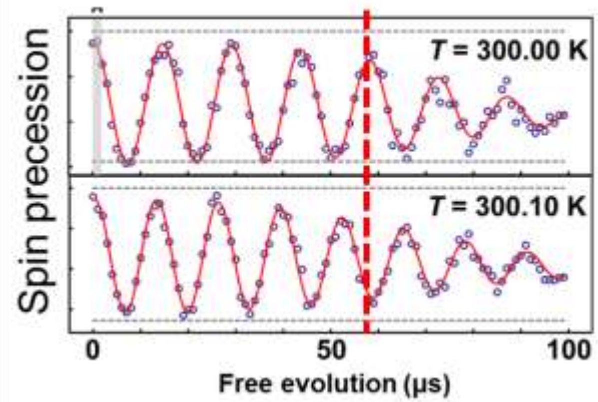


Nat. Phys. **7**, 459 (2011)

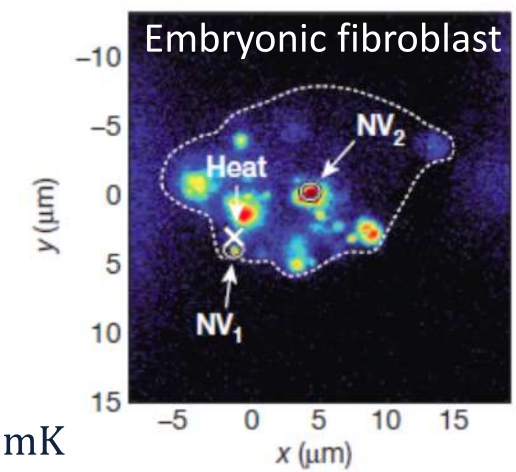


$$\eta \sim 200 \frac{\mathrm{V}}{\mathrm{cm}\sqrt{\mathrm{Hz}}}$$

Temperature



Phys. Rev. X**2**, 031001 (2012)
PNAS **110**, 8417 (2013)

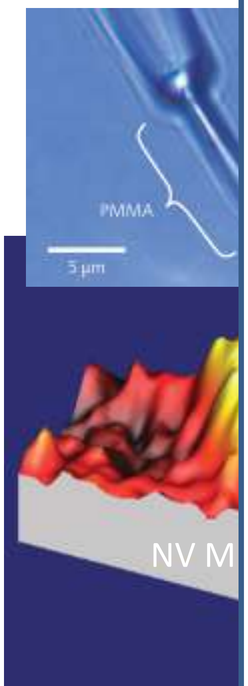


$$\eta \sim 7 \frac{\mathrm{mK}}{\sqrt{\mathrm{Hz}}}$$

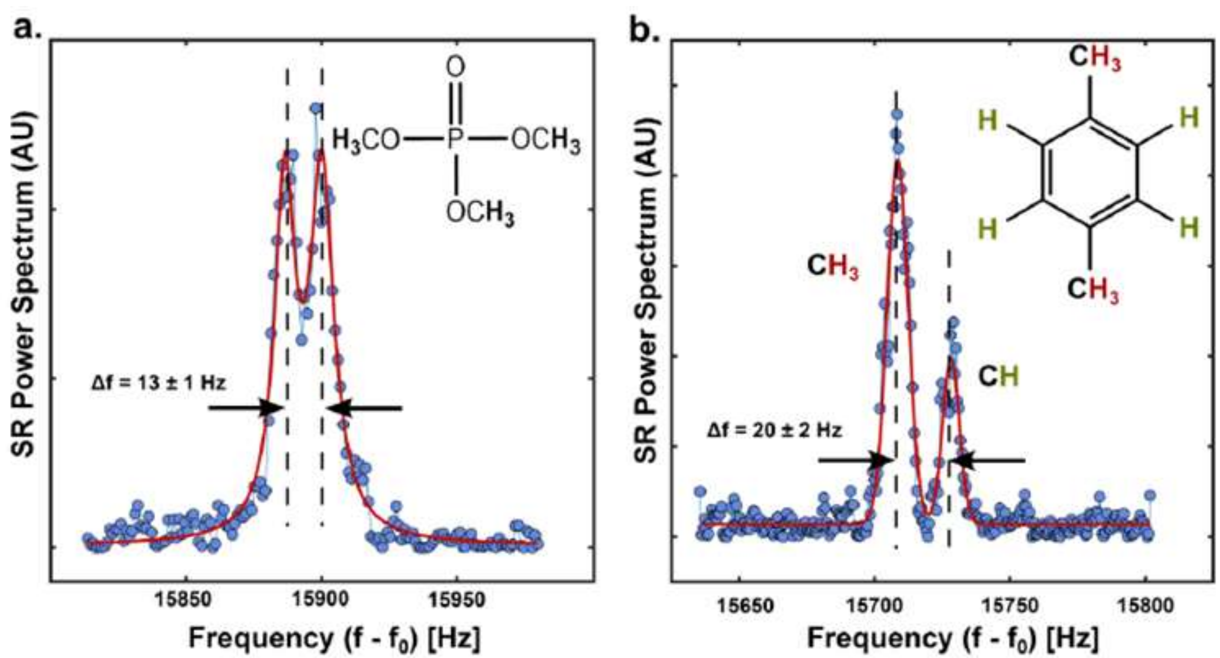
Nature **500**, 54 (2013)

Nanometer-scale NMR imaging

Proto



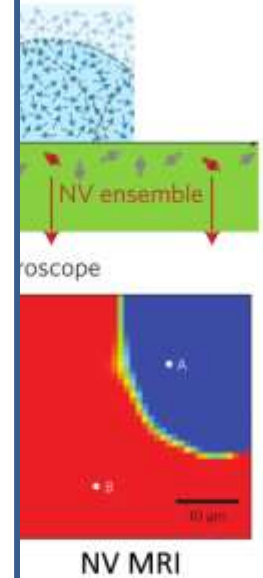
Rugar D. *et al.*
10, 120-124 (2



- Measured trimethyl phosphate J-coupling and xylene chemical shift
- NMR j-coupling at micron scale
- ~10 hours of signal averaging; 1 picoliter; ~3 Hz resolution

arxiv: 1705.08887

R imaging of
pecies



, Nature Nano.

Many geometries have had success making nanoscale nuclear spin density images

Recent demonstrations of single proton sensitivity

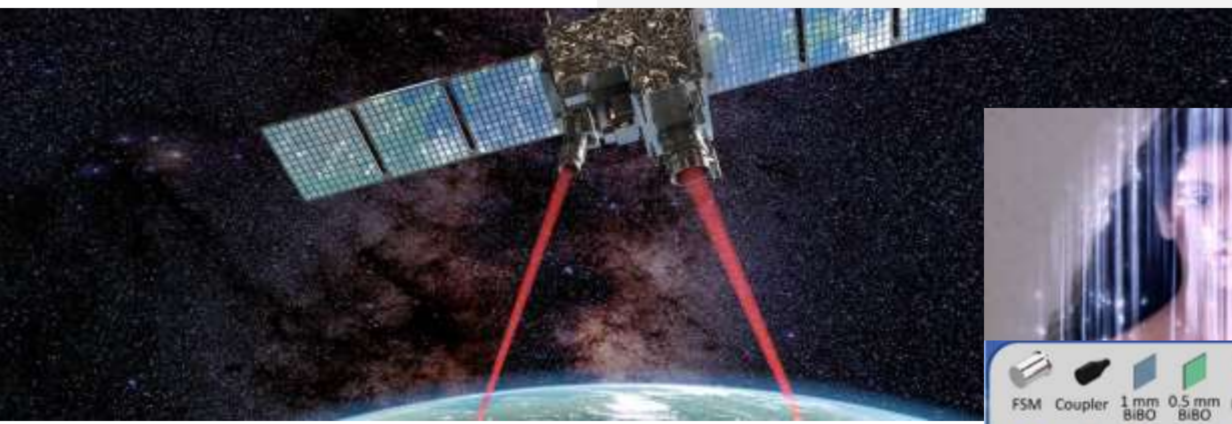
Recent large-scale demonstrations

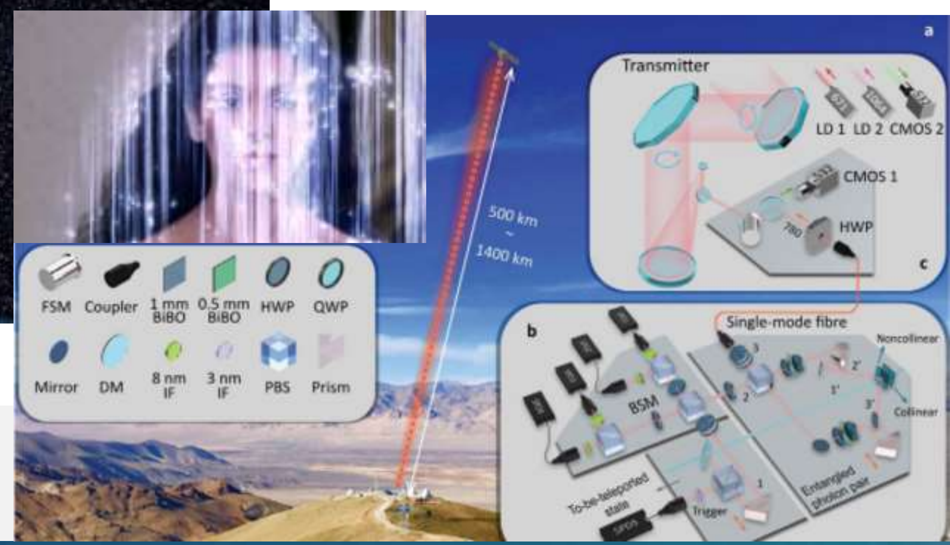
Loophole-free Bell inequality test & entangled electrons > 1 km

Nature **526**, 682 (2015)

“Satellite-based entanglement distribution over 1200 kilometers”

Science **356**, 1140 (2017)





“Ground-to-satellite quantum teleportation” (1400 km) *arXiv*:1707.00934

Global engagement: national initiatives

TU Delft National Project
2020 goal
Four-node quantum internet

European Quantum Technology Flagship (2018)

Commitments > 2B$ over 5-10 years

Industrial engagement: focused

THE UNIVERSITY OF CHICAGO | Institute for Molecular Engineering

IBM

Google

Microsoft

HRL

intel

NORTHROP GRUMMAN

Google Plans to Demonstrate the Supremacy of Quantum Computing

By the end of 2017, Google hopes to make a 49-qubit chip that will prove quantum computers can beat classical machines

By RACHEL COURTLAND
Posted 24 May 2017 | 15:00 GMT

nature

COMPUTING

IBM Will Unleash Commercial "Universal" Quantum Computers This Year

The cloud-based "IBM Q" service is not expected to outperform conventional computers—yet

By Davide Castelvecchi, Nature on March 6, 2017

Summary and outlook

Number of scientific discoveries

- experiment and theory working together driving research
- several emerging physical systems with exquisite control
- applications in computing, communication, and sensing
- impressive success with density functional theory

Challenges for materials

- creating materials with highly coherent quantum states
- developing theoretical tools to search for novel materials
- constructing atomic-scale characterization/imaging techniques
- explore layered 2D and hybrid quantum materials