Characterizing Quantum Technologies

Joel Wallman

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- Jaron Huq (UW)
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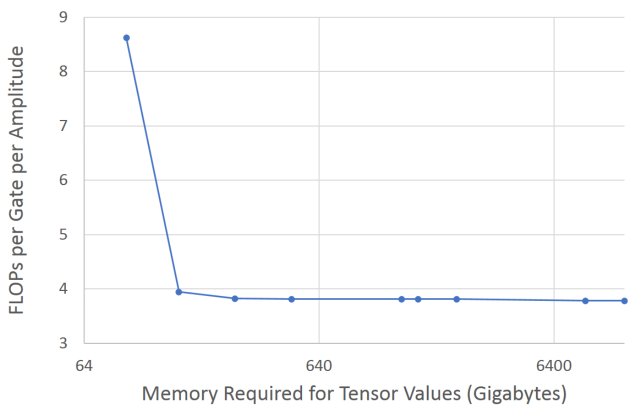
- Yuval Sanders (Macquarie University)
- Barry Sanders (UCalgary)

TQT Transformative Quantum Technologies

CANADA FIRST RESEARCH EXCELLENCE FUND

Characterizing Quantum Technologies

Quantum computers are enabling because of their complexity



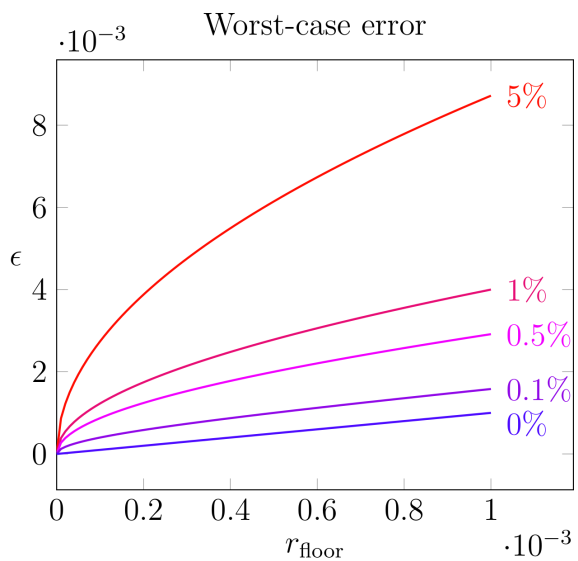
Memory/CPU requirements for simulating a 49-qubit quantum computer
E. Pednault, *et al.*, arXiv:1710.05867

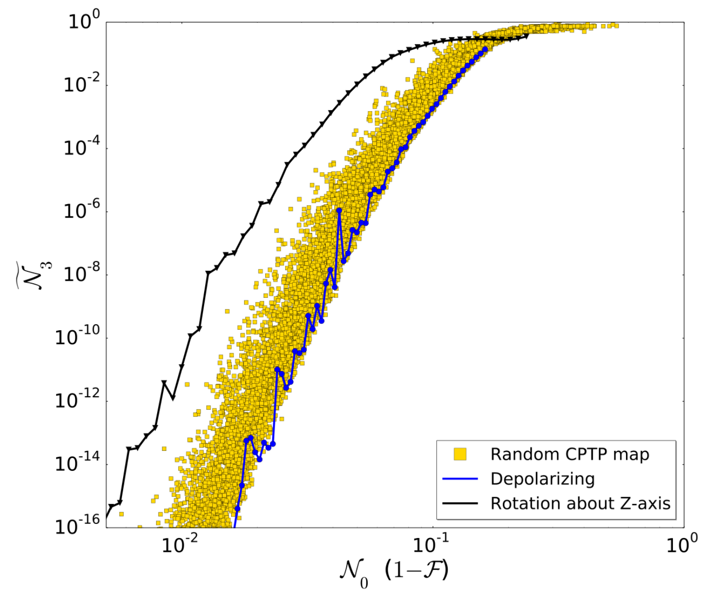
How do you verify they are performing correctly?

- Full characterization (e.g., gate-set tomography)? Defeats the purpose
- Don’t? Potentially dangerous
- Partial characterization? Need to ensure you characterize the relevant performance!

Average gate infidelity

Infidelity is generally loosely correlated with performance…





Error as a percentage of T1/T2 fidelity
Y. Sanders, JJW, B. Sanders, NJP 18, 012002 (2015)

Loosely predicts logical error rates under quantum error correction
P. Iyer and D. Poulin, arXiv:1711.04736

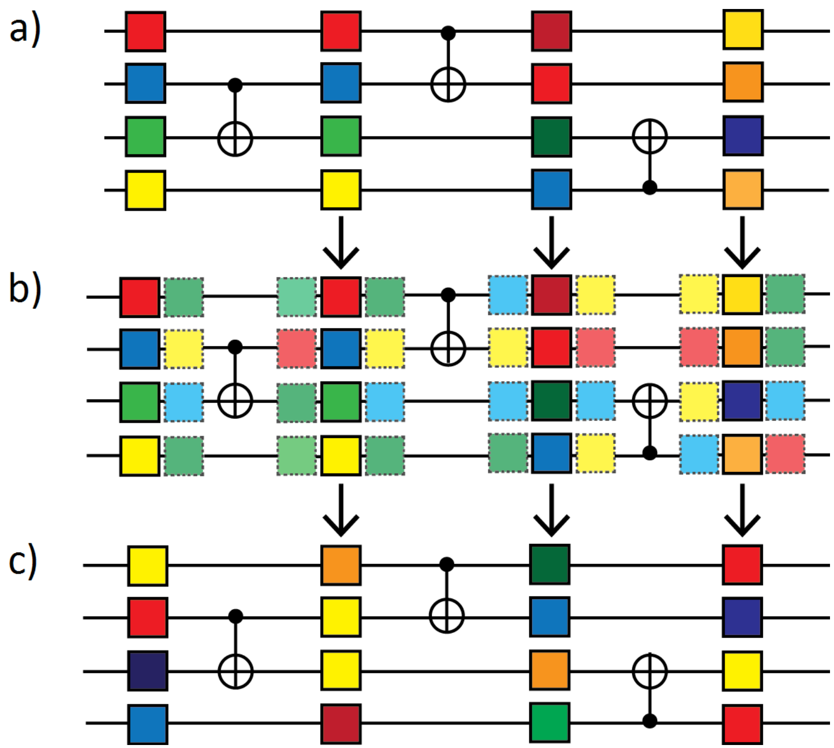
Randomized compiling for universal circuits

Except: infidelity is strongly correlated with performance for stochastic noise

Randomized compiling:

- organize circuits into a canonical form
- insert random gates at each time step
- insert corrections at the next time step
- Compile to the same gate depth

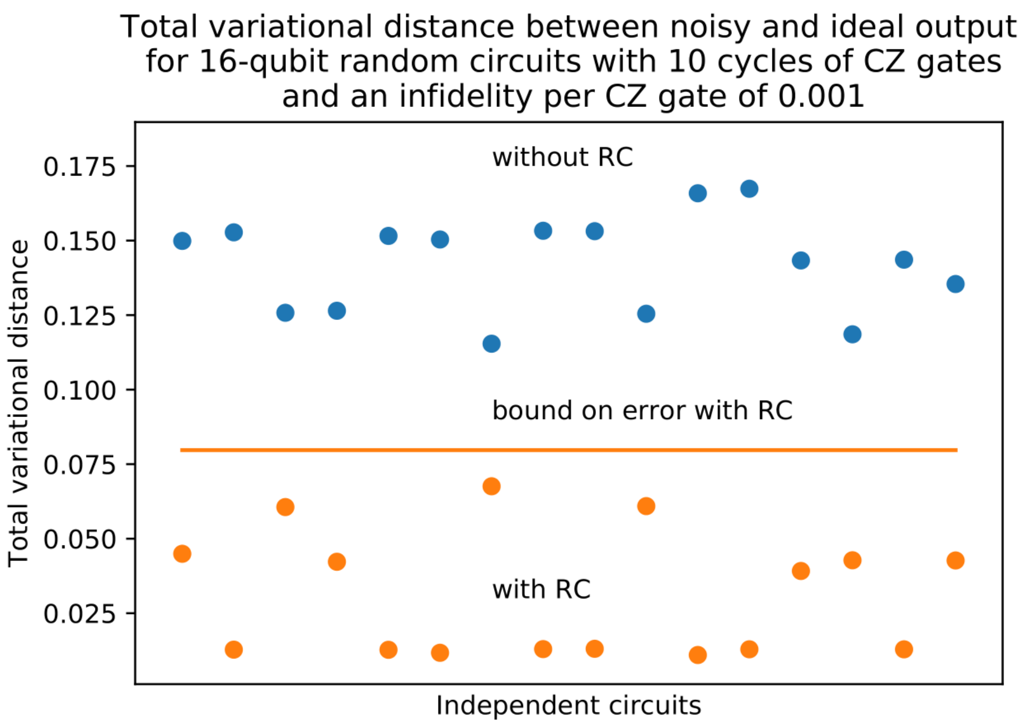
JJW and J. Emerson, PRA 94, 052325 (2016)



Randomized compiling for universal circuits

Benefits:

- Removes coherent errors
- Makes errors more predictable
- Implements randomized dynamical decoupling
- No extra overhead on quantum hardware



Predicting performance of randomized compiling

Noise under randomized compiling is stochastic, so can be accurately predicted by the infidelity

Cycle benchmarking:

- Repeating fixed cycle m times
- Apply randomized compiling
- Sample a set of input states
- Apply extra randomization to decouple state-preparation and measurement errors
- Vary m and fit decay rate for each input
- Infidelity is proportional to the average decay rate over inputs

Conclusions

- Randomized compiling can make quantum computers more reliable with no additional quantum hardware

- Using cycle benchmarking, we can accurately and efficiently predict the performance of universal, large scale quantum computers that use randomized compiling

Future work:

- Experimental demonstrations

- Reconstruct stochastic noise channel to optimize error rates

Transformative Quantum Technologies

Institute for Quantum Computing

The Road Toward a Medium-Scale Quantum Computer

Matteo Mariantoni

Laboratory for Digital Quantum Matter

Institute for Quantum Computing and Department of Physics and Astronomy

CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE

Why Build a Quantum Computer

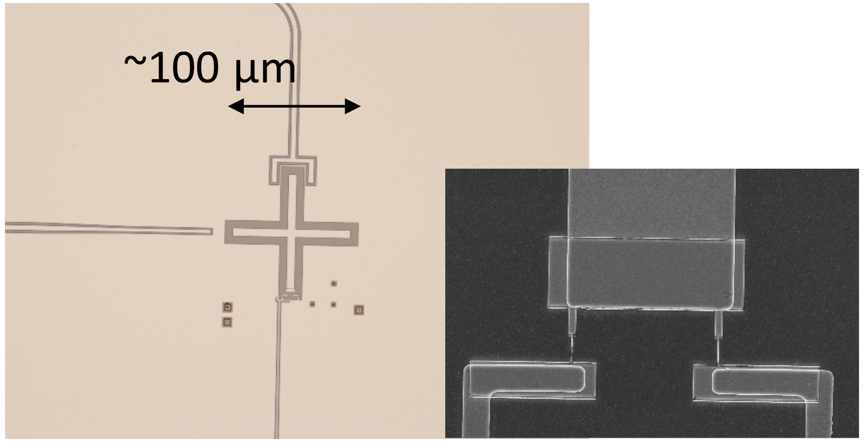
- medium scale ~ 100 qubits

- Cryptography (break RSA-2048)
- *Quantum simulations (quantum chemistry)*
- Search and optimization
- Linear equations
- Quantum walks (Markov chains)
- *Quantum annealing*
- *Machine learning*

60’s not many people thought classical computers would lead to all present applications

Many Implementations

- Nuclear-magnetic resonance
- Trapped ions
- Quantum dots
- …
- Superconducting circuits



Laboratory for Digital Quantum Matter qubit

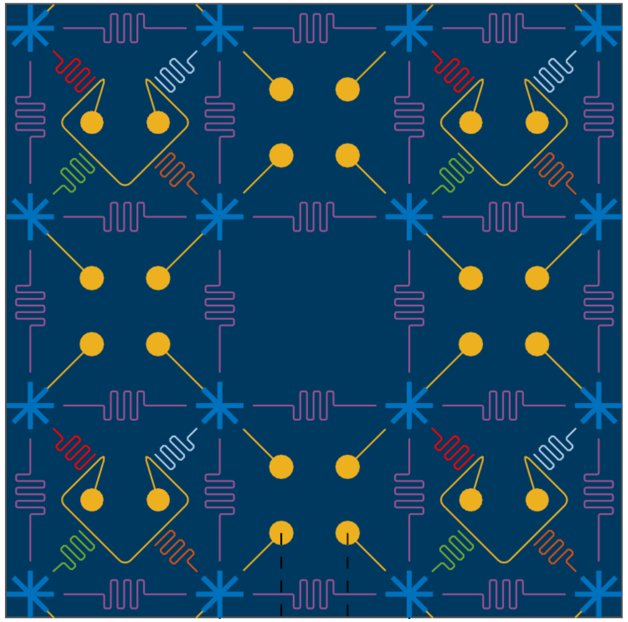
- Nonlinear LC oscillator at about 5 GHz
- On-chip fabrication similar to CMOS, Al/Si
- Controlled with microwave signals
- Cooled to about 10 mK

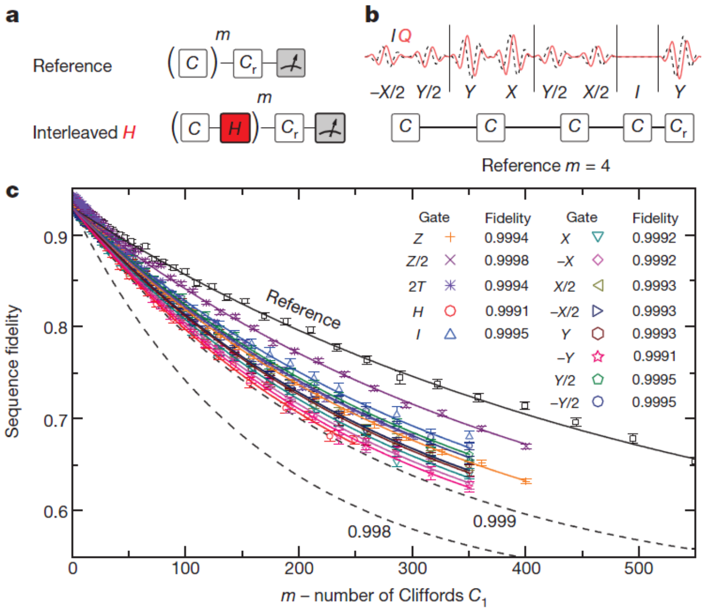
Two Challenges

- Scalable
- Low-error rates

J.M. Martinis, npj Quantum Information **1**, 15005 (2015)

R. Barends, Nature **508**, 500 (2014)

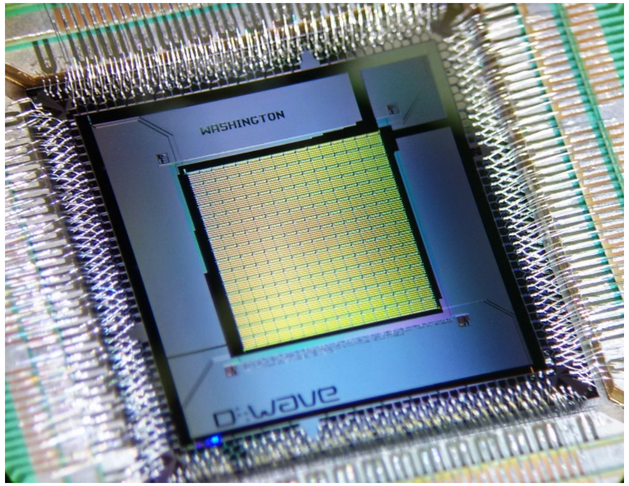




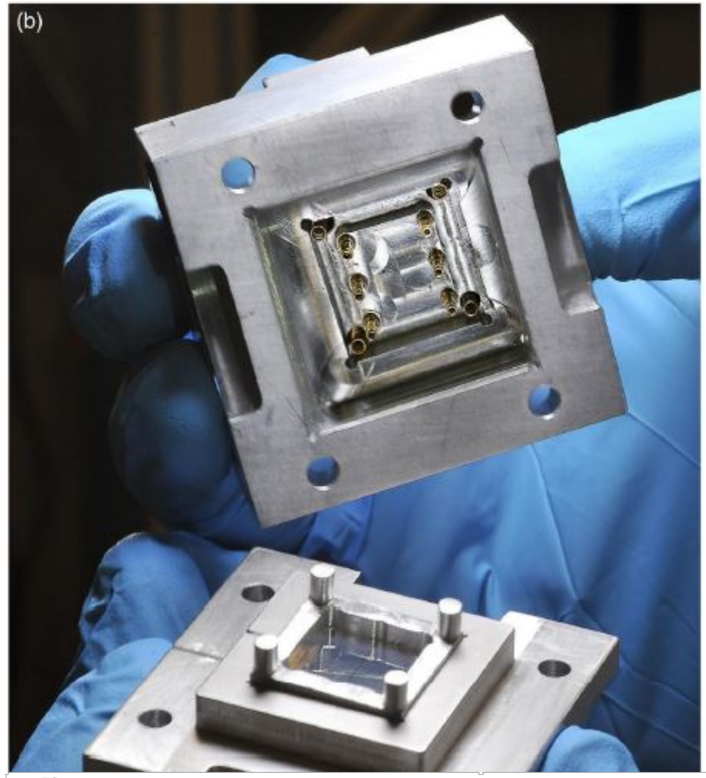
J.H. Béjanin, T.G. McConkey,…MM, Phys. Rev. Appl. **6**, 044010 (2016)

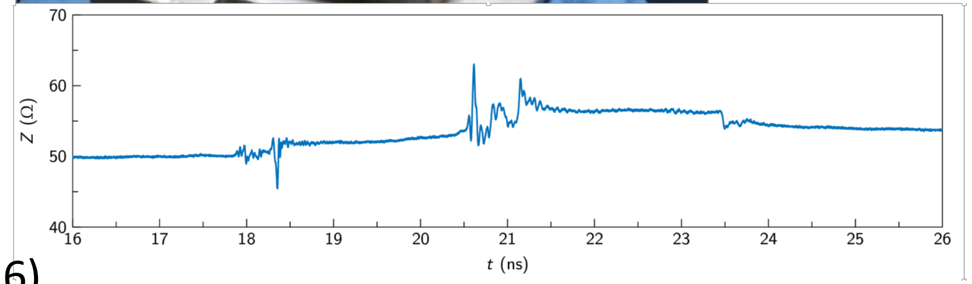
The Quantum Socket

BLG file: PAT 86891-0 Reference 7435
US Patent Pending



D-Wave Systems Inc.

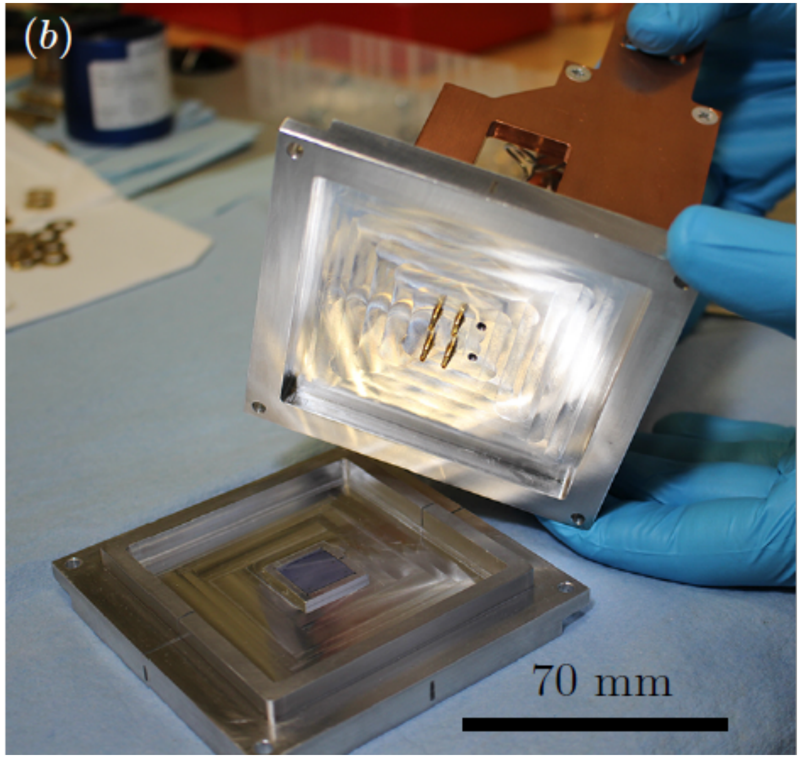


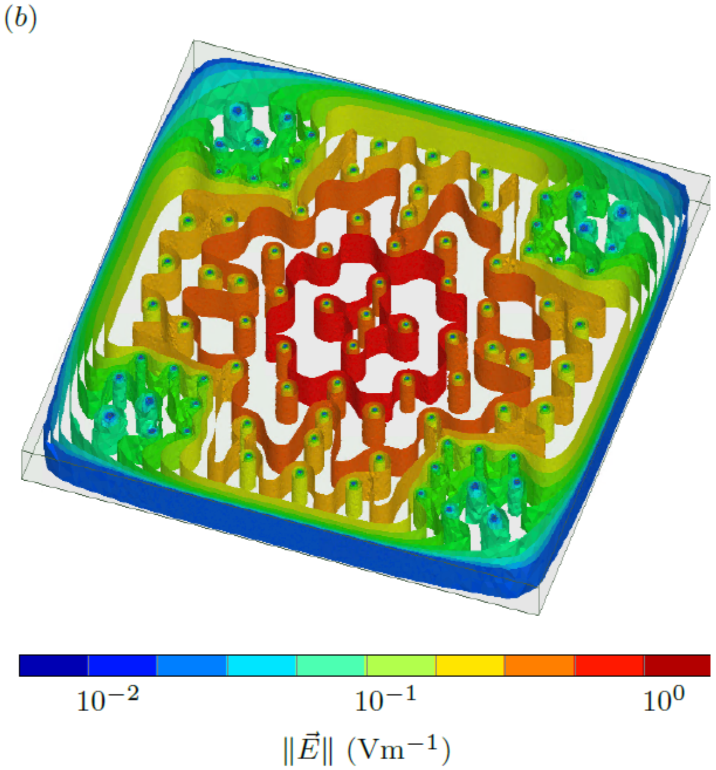


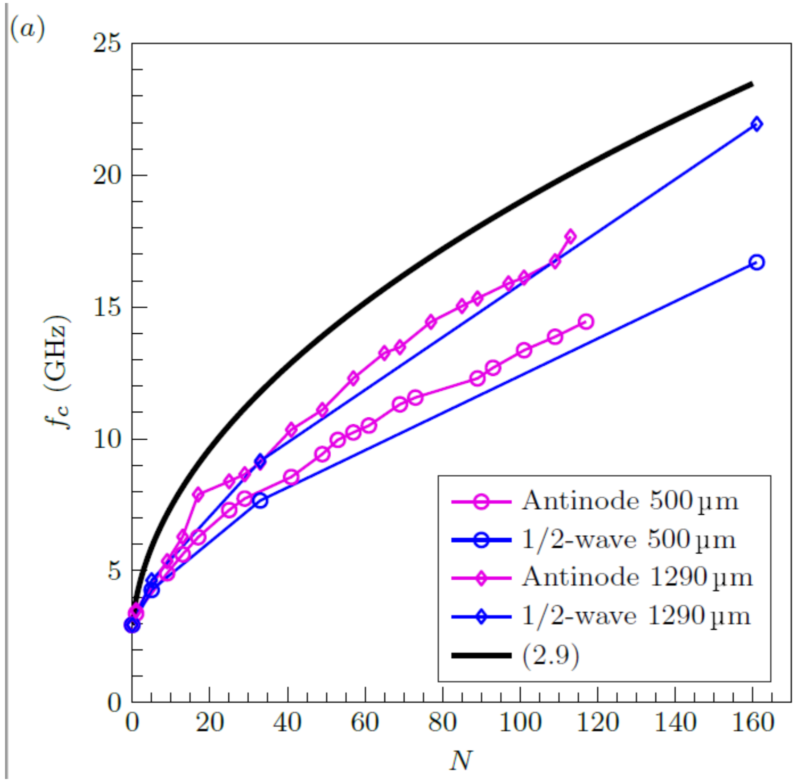
J.H. Béjanin, T.G. McConkey,…MM, Phys. Rev. Appl. **6**, 044010 (2016)
J. Reinhart,…MM, submitted (2017) – TQT Project

The Large-Scale Quantum Socket

S. Sheldon *et al.*, arXiv:1703.04501



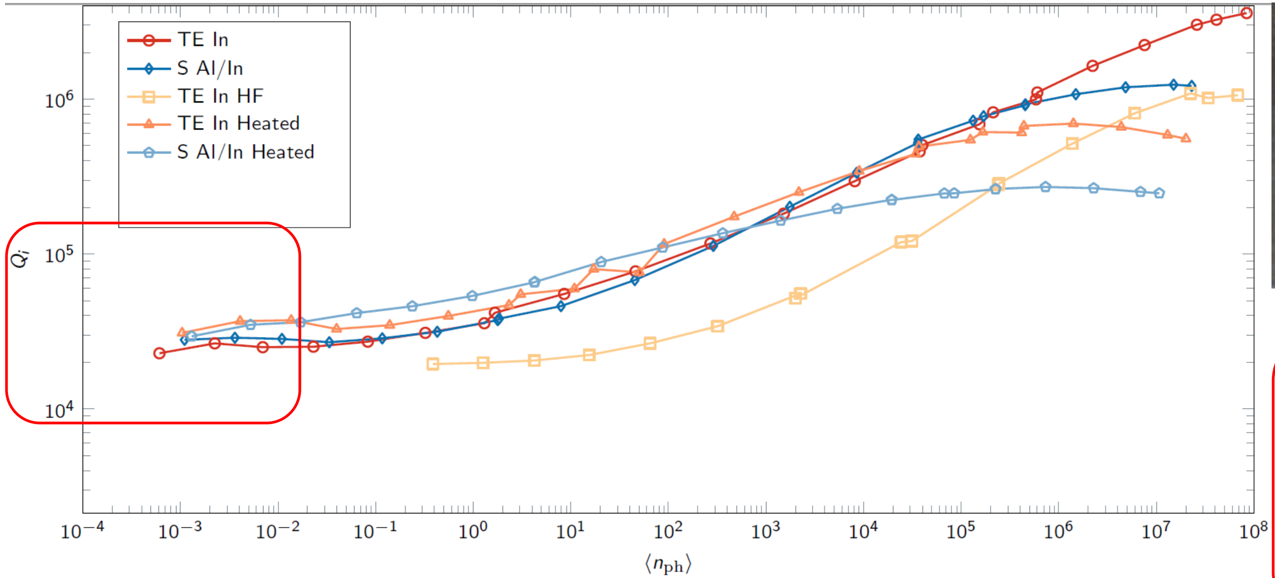




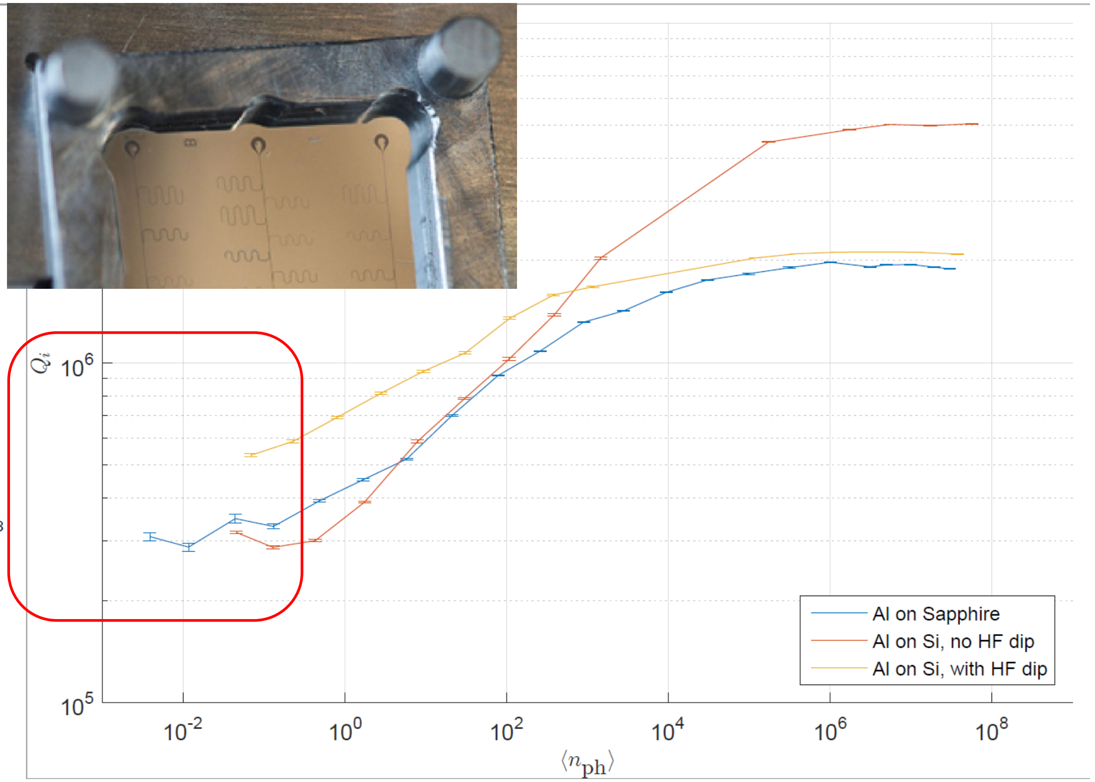
can host up to ~100 qubits

T.G. McConkey,…MM, arXiv:1710.04590 submitted to Quantum Science and Technology (2017) – TQT Project

Improving materials



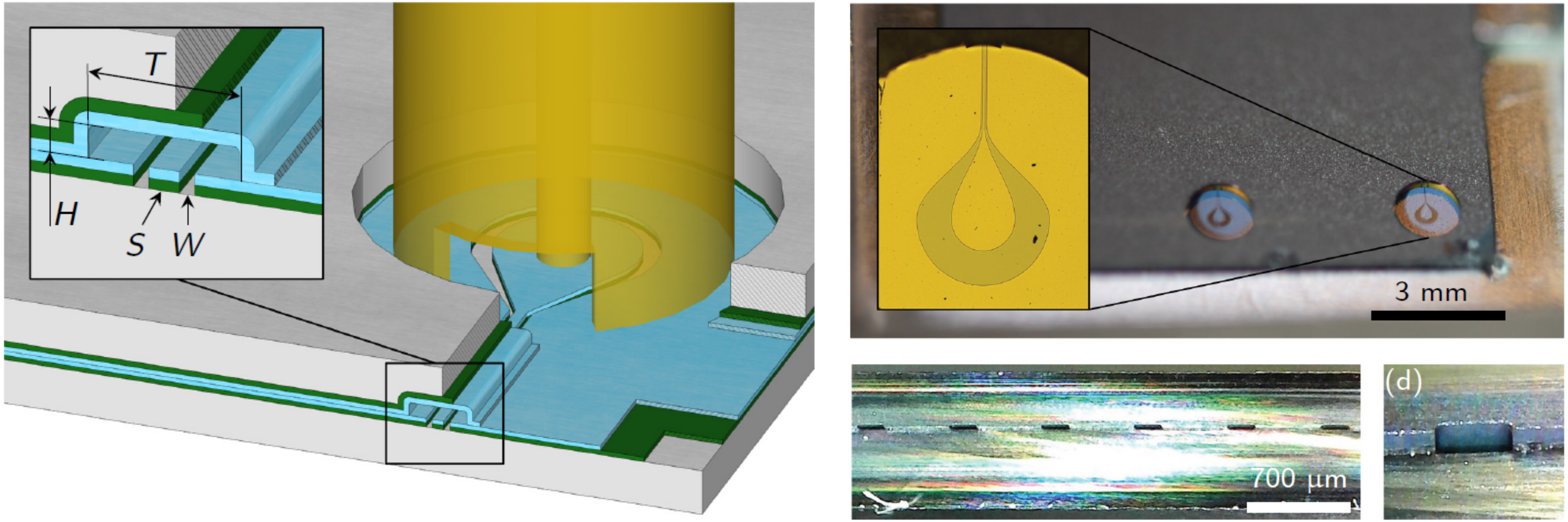
C.R.H. McRae,…MM, in prep. (2017) – TQT Project
J. Tournet,…,MM, Z.R. Wasilewski, SUST **29**, 064004(2016)



C.T. Earnest,…MM, in prep. (2017) – TQT Project

- Measure superconducting resonators
- Quality factors
- Classical and quantum regimes
- Loss: Two-level states (OH molecules)

Thermocompression bonding



C.R.H. McRae,…MM, App. Phys. Lett. **111**, 123501 (2017)

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Quantum Materials for Spin Information Processing

Guoxing Miao

Electrical and Computer Engineering
Institute for Quantum Computing (IQC)
University of Waterloo

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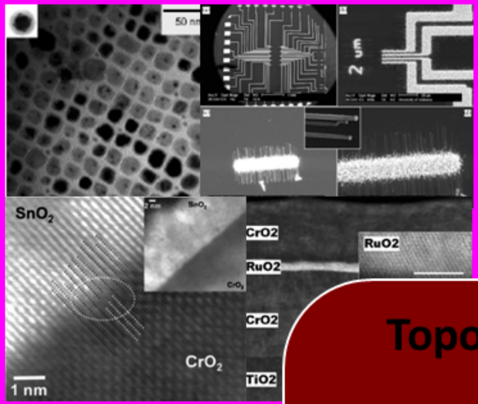
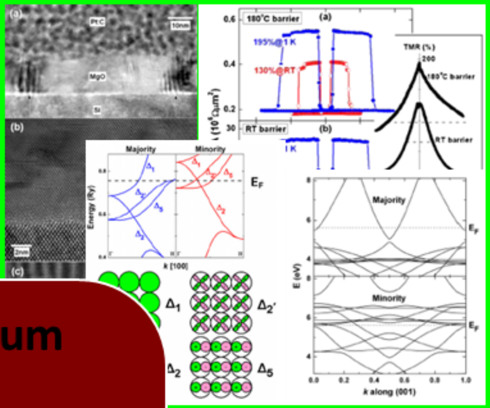
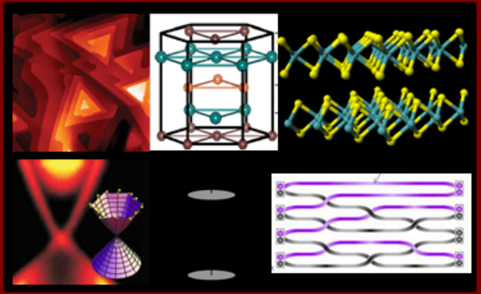
Materials Science



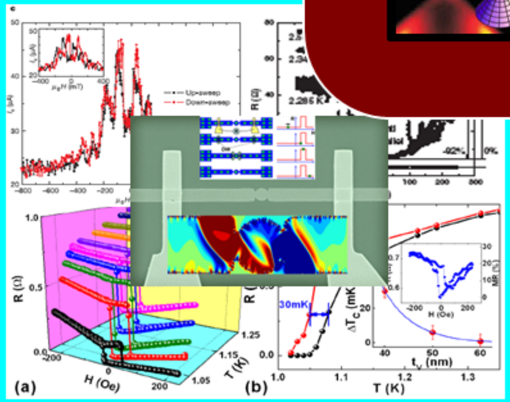
Nano-Electronic Device



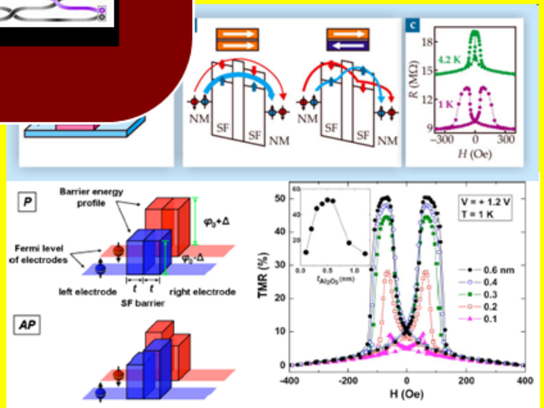
Topological Quantum Computing



Superconductivity



Magnetic Semiconductor



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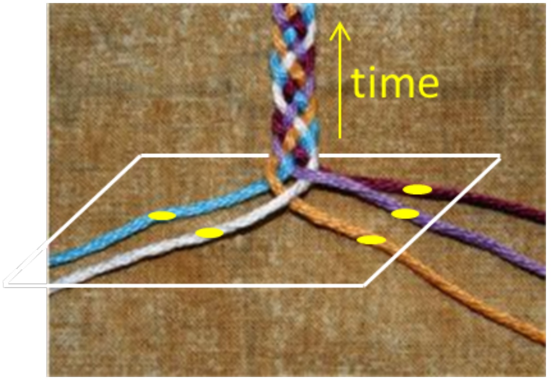
1. Topological Quantum Computing

Topological Quantum Computing is based on braiding operations with *anyons* obeying non-Abelian statistics. It is innately error-tolerant because the braided pairs are spatially well separated, ie., non-local encoding;

(Kitaev, 1997)



Majorana Fermions are exactly such anyons with themselves being their own antiparticles. A Majorana can be considered "half a Fermion", and exchanging two of them leads to a phase change of $\pi/2$ on the system. *Spinless p-wave superconductors*, with electrons forming spin triplet Cooper pairs, are predicted to host the Majorana Fermions in their vortex cores;

(Majorana, 1937) (Read & Green, 2000)

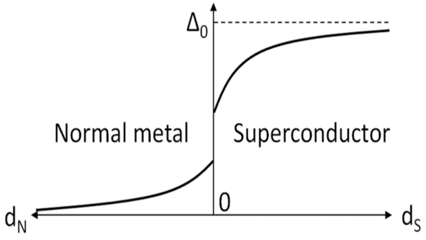
In reality, however, p-wave superconductors are extremely rare and very fragile due to the broken time-reversal-symmetry. For example, Sr_2RuO_4, the most promising *p*-wave superconductor, quickly loses its superconductivity in the thin film format. What should we do?

Simulating Majorana Fermions on Topological Superconductors

Building “Majorana Fermions”

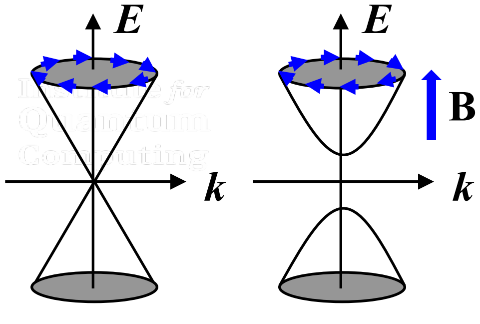
Proximity induced *p*-wave superconductors on Topological insulators

Fu & Kane, PRL 2008



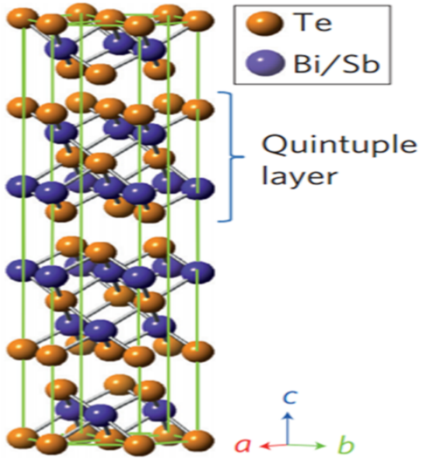
Design criteria:

- Helical Dirac Fermions from topological insulator – spinless;
- Proximity from superconductor – particle-hole symmetry;
- Exchange field from magnetic insulator – opens up a gap precisely at the Dirac point, allows selecting only the desired p_x+ip_y state;
- Vortex – localized end mode;



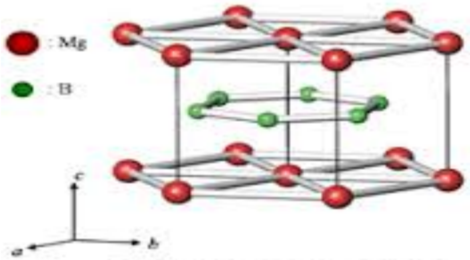
Helical Dirac spin states

Zeeman gapping



Error-tolerant: nonlocality & topology

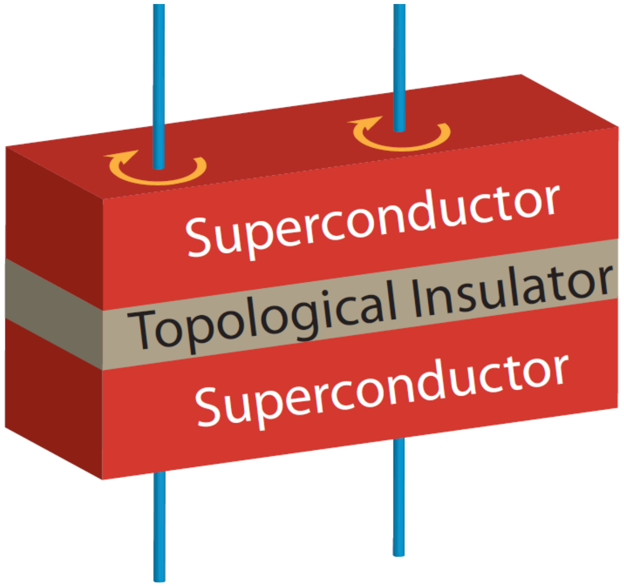
Majorana fermion creation

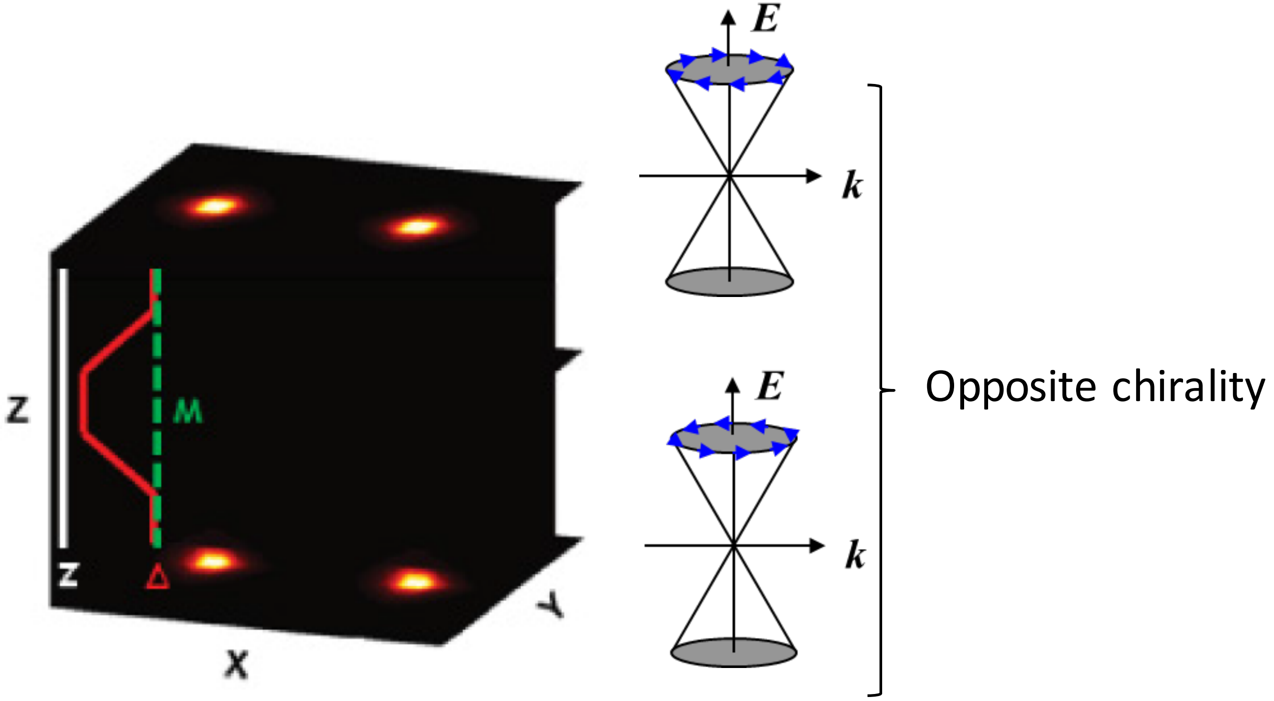


Materials we are after:

Bi-Sb-Te (BST) w/ Cu/Cr/Ca
MgB_2 s-wave superconductor
EuO magnetic semiconductor

SC/TI/SC Heterostructures



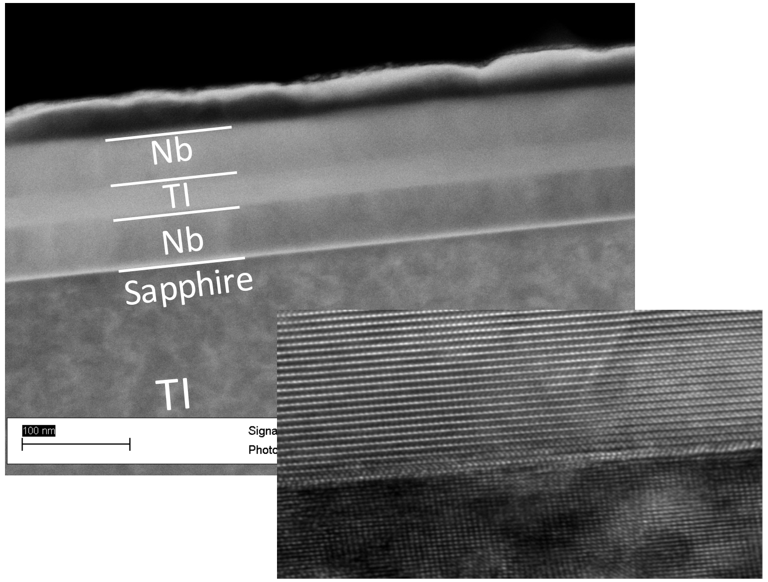


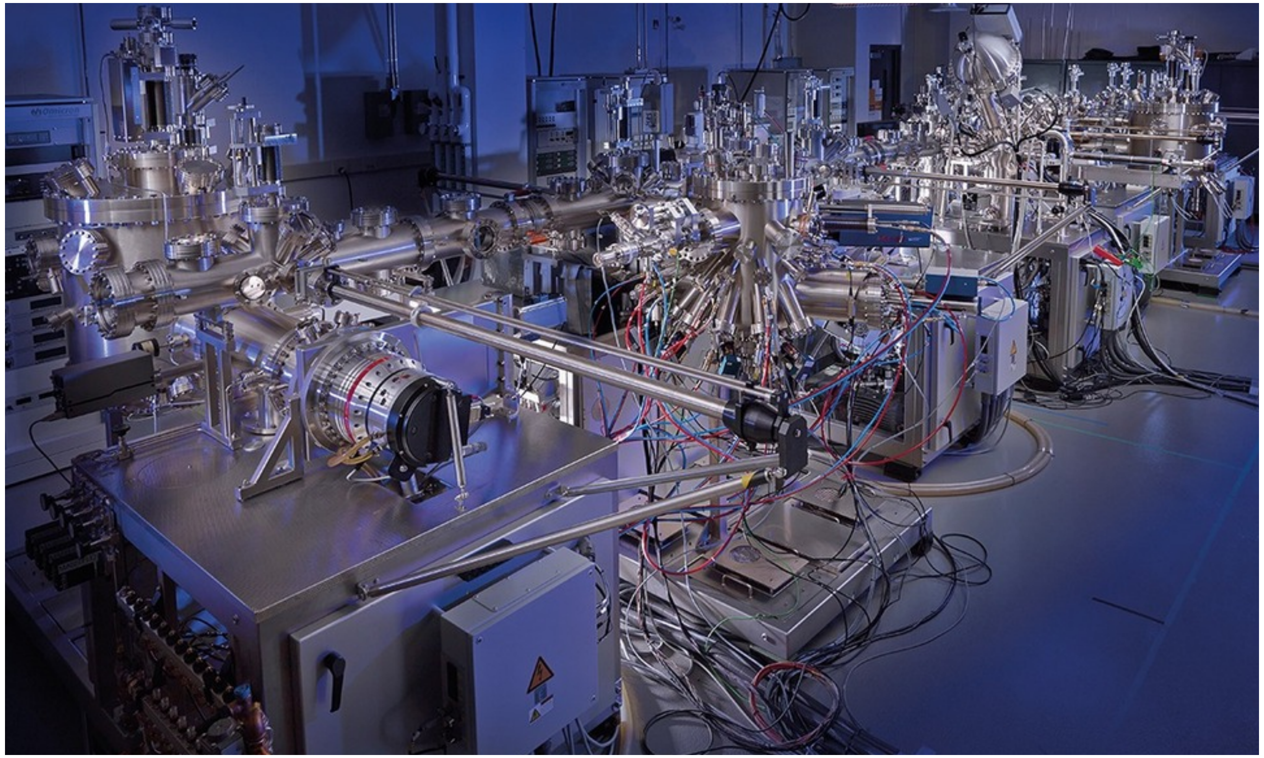
In a sandwiched heterostructure SC/TI/SC, we can induce a 2D topological superconducting state at each interface by proximity effect. Majorana fermions are predicted to localize at two ends of the magnetic flux lines penetrating this heterostructure.

C.-K. Chiu, M. J. Gilbert, and T. L. Hughes, *Phys. Rev. B. 84, 144507 (2011)*

Experimental Methods:

Growth of Nb/$(Bi_{1-x}Sb_x)_2Te_3$/Nb





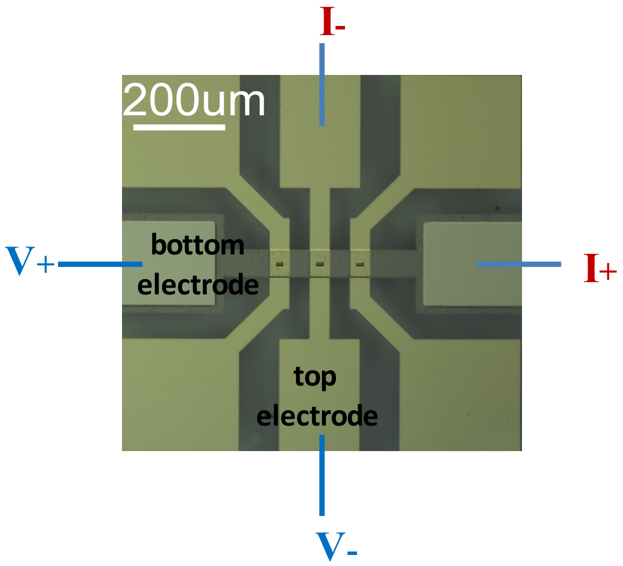
- $(Bi_{1-x}Sb_x)_2Te_3$ (<u>BST</u>) was grown by molecular beam epitaxy (MBE) in ultra-high-vacuum (10^{-11}mbar)

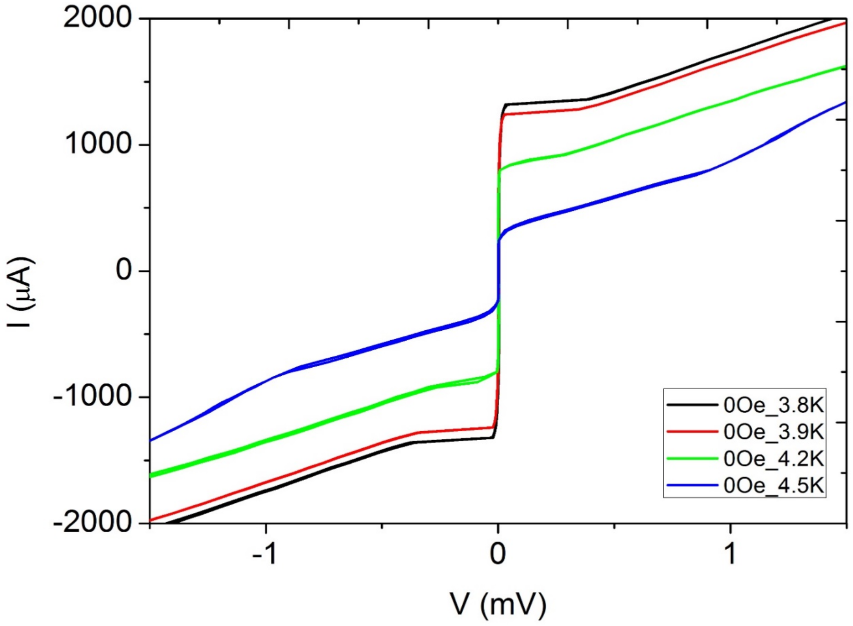
  x=0.60 carrier density $n < 1.0 \times 10^{13}\ cm^{-2}$ (77K)

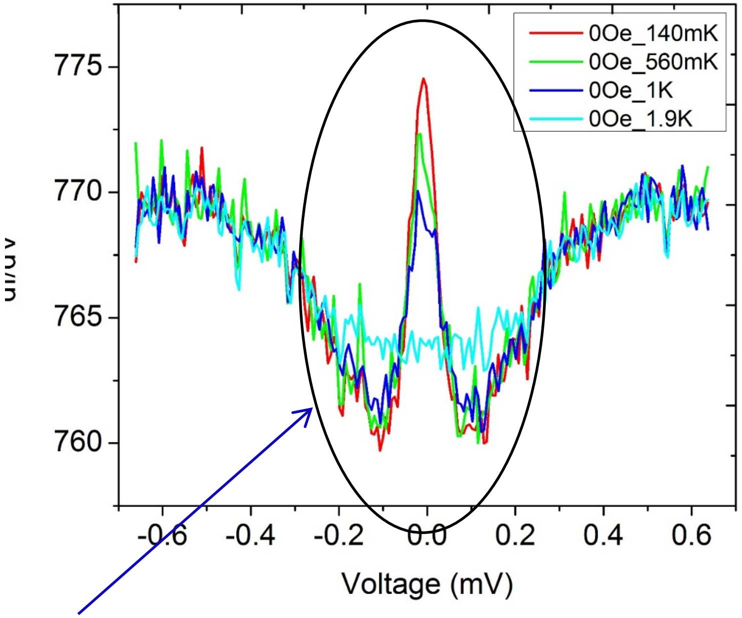
- Nb was magnetron sputtered. Growth chambers are interconnected by vacuum transfer line, which guarantees clean interface between layers

Example Results:

- 50nmNb/7nmBST/50nmNb
- Junction size 6 µm × 6 µm

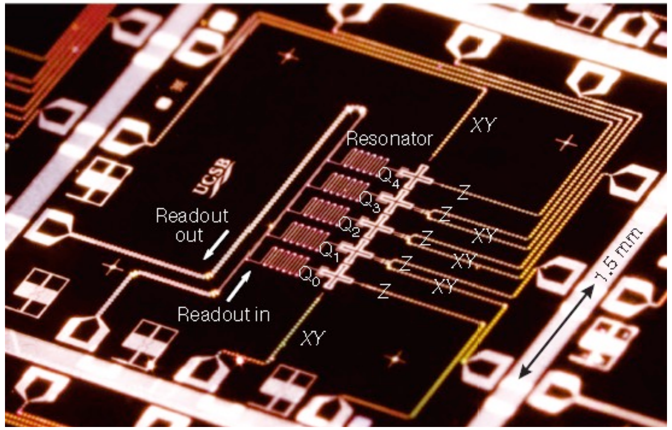




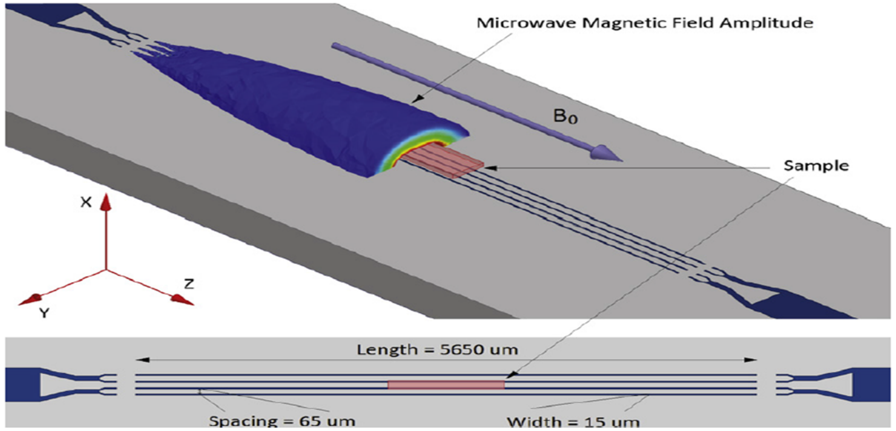


Majorana zero modes?

2. Composite Superconductor Resonators



Supercondutor Circuits
(Josephson junction qubits)

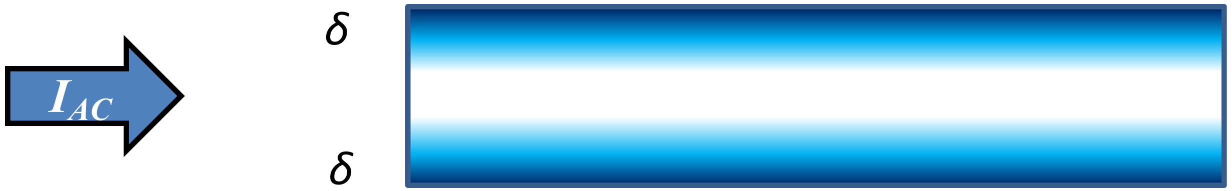


Electron Spin Resonance
(nuclear spin qubits)

- Coherent storage of quantum information;
- Couple different quantum systems;
- Sensitive readouts;

Wait, superconductors have loss?

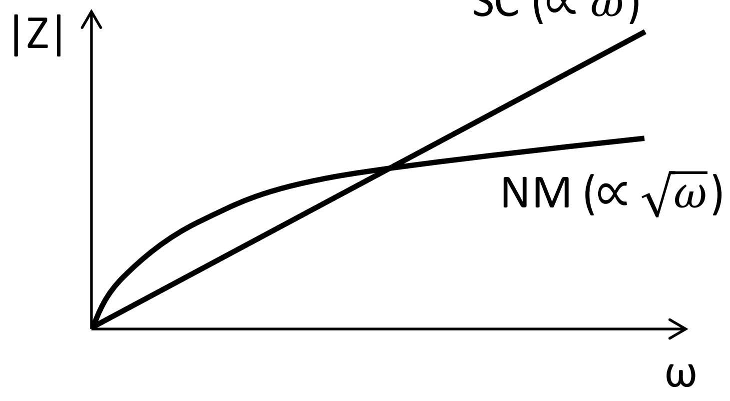
Background: AC current has a ***skin effect*** when travelling in a conductor



Skin depth $\delta_{normal} = \sqrt{\frac{2}{\mu\omega\sigma}}$

e.g. Cu at RT and 10 GHz, δ ~ 650 nm
(~ 20 nm at helium temperatures)

Concept 1: a superconductor does have finite impedance in AC

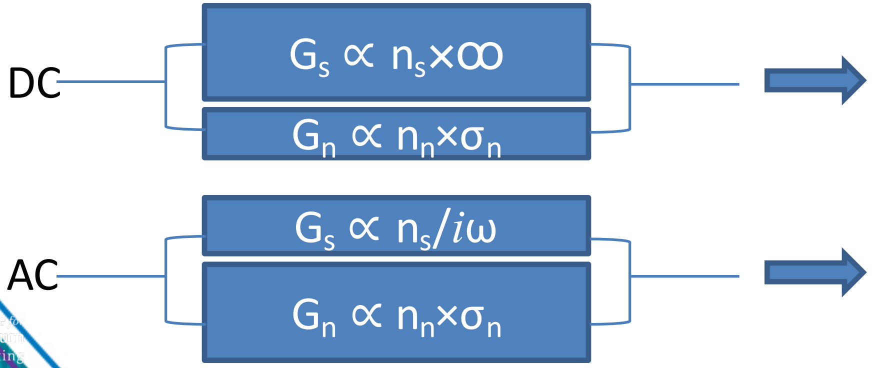


Electron equation of motion: $\frac{d\vec{v}}{dt} = \left(-\frac{e}{m}\right)\vec{E} - \frac{\vec{v}}{\tau}$; the Fourier component for $e^{-i\omega t}$

leads to: $\vec{J} = \left(\frac{\sigma_0}{1+i\omega\tau}\right)\vec{E}$

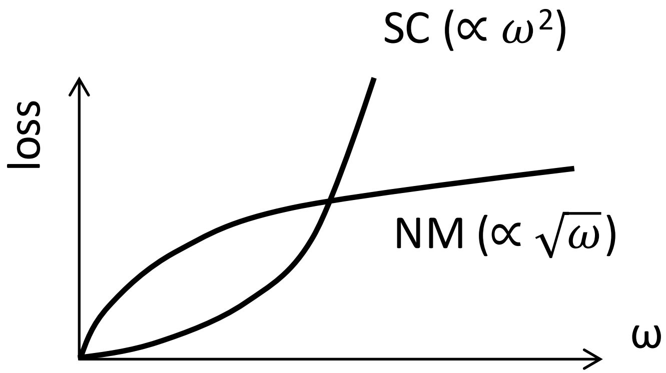
For a normal metal, even at LT, $\omega\tau \ll 1$, $\sigma \to \sigma_0$ and $Z \propto \sqrt{\omega}$;
For a superconductor, $\tau \to \infty$, $\sigma \propto 1/i\omega$, δ is constant, thus $Z \propto i\omega$ (***Finite impedance***, ie, "kinetic inductance")

Concept 2: a superconductor does have dissipation in AC



Z = 0,
ie, superconducting

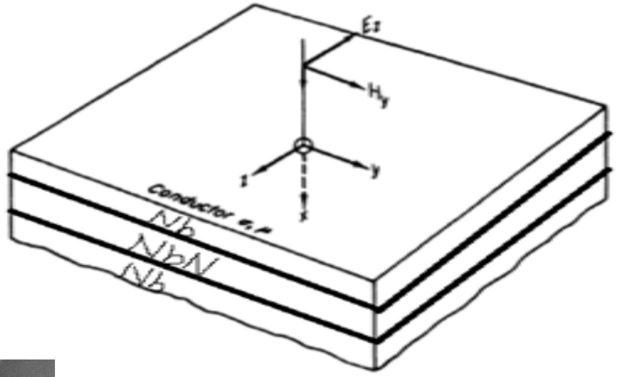
$\mathrm{Re}(Z) \propto \omega^2$

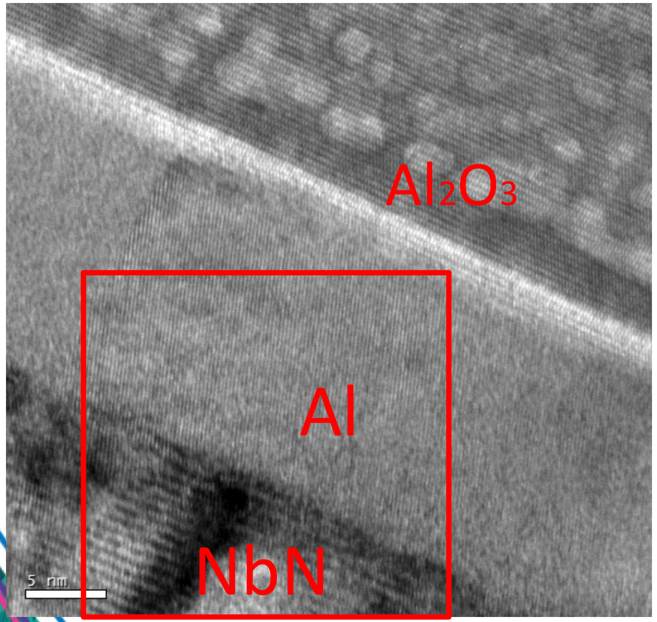


Composite superconductor resonators

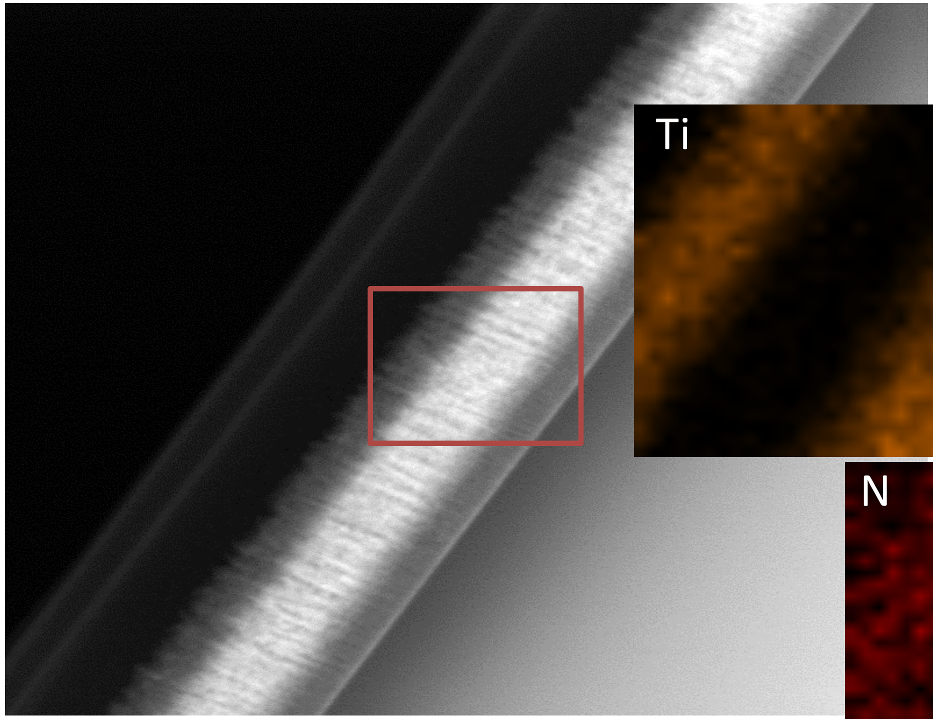
- Design concepts:

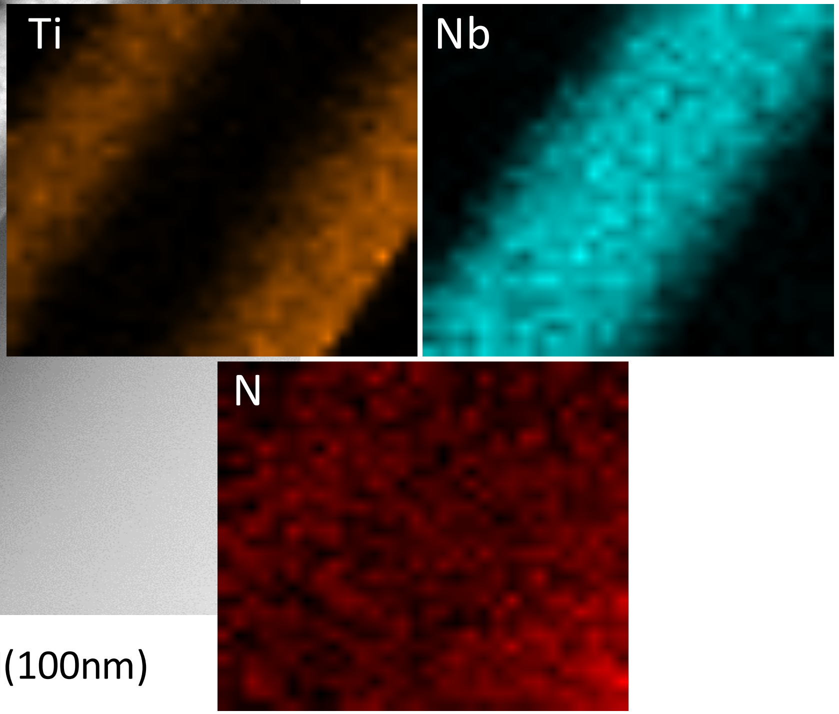
- Core layers from higher H_c, T_c materials to boost superconductivity strengths;
- Surface layers constructed from low loss materials, with long coherence length and short penetration depth, for effectively mediate proximity and concentrate microwave;





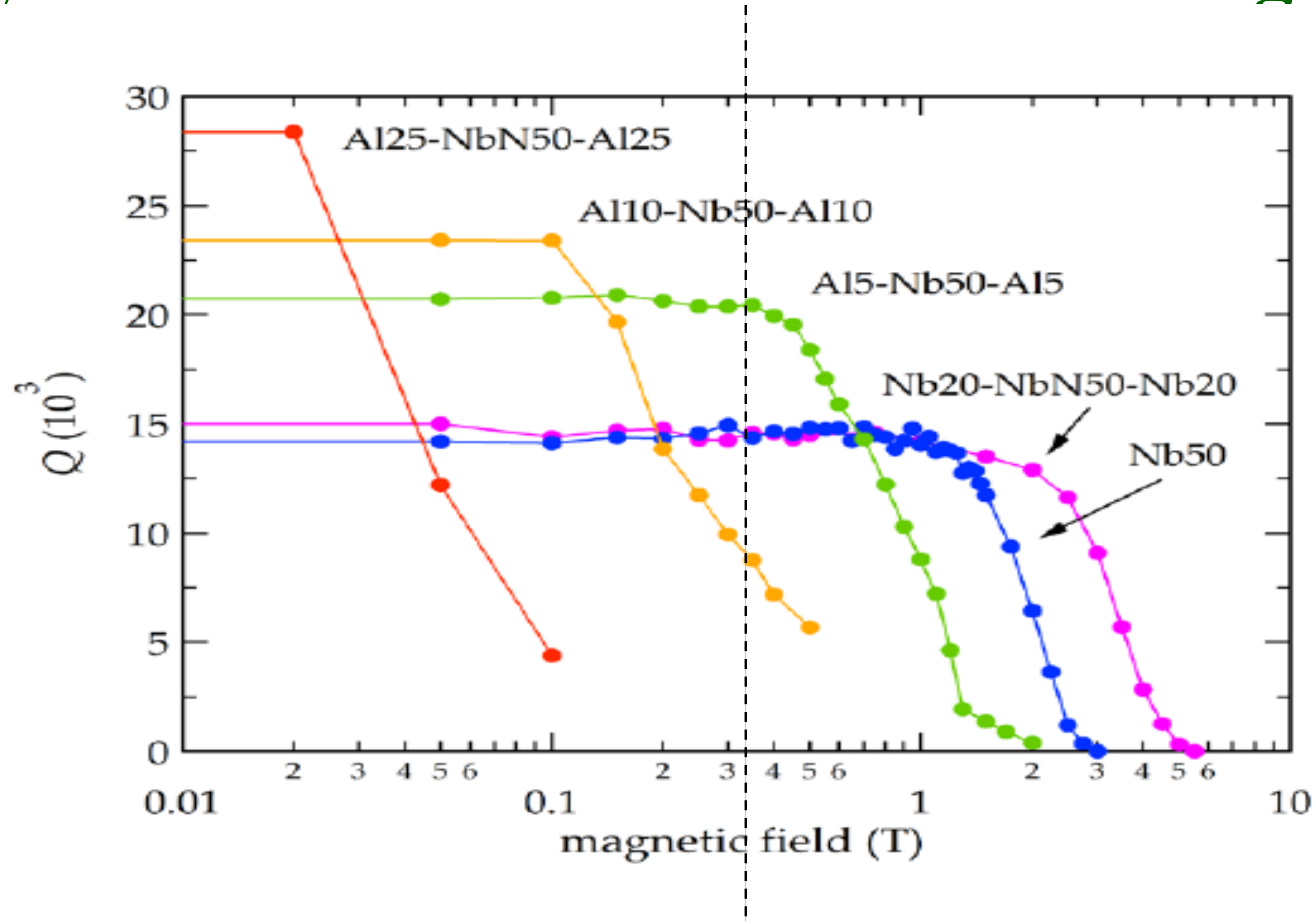
Al(20)-NbN(50)-Al(20)





TiN-TiNbN-NbN-TiNbN-TiN(100nm)

Summary of the various resonators under magnetic fields

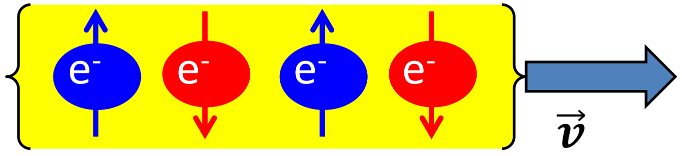


Requires the best Q, at 0.35T

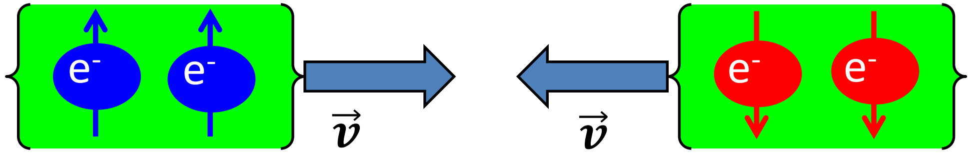
Winner right now: Al/Nb/Al

3. Spin Polarized Transport

- Pure spin current does not generate Joule heating



A normal “charge” current
Voltage high/low
Resistive



A pure “spin” current
Dipole up/down
Diffusive

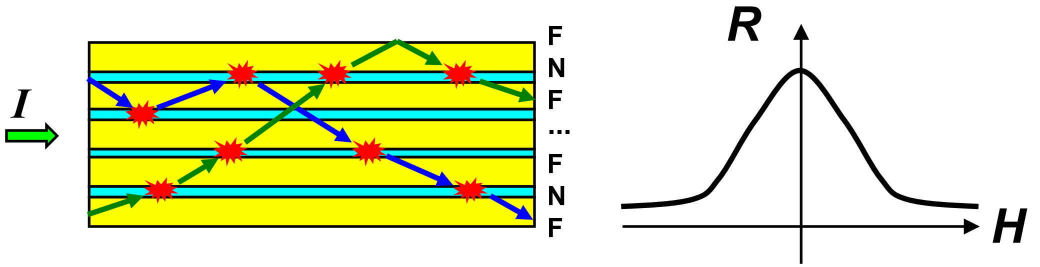
- An additional information channel, and an additional information control nob
- Non-volatile, durable, robust, low energy information storage and processing

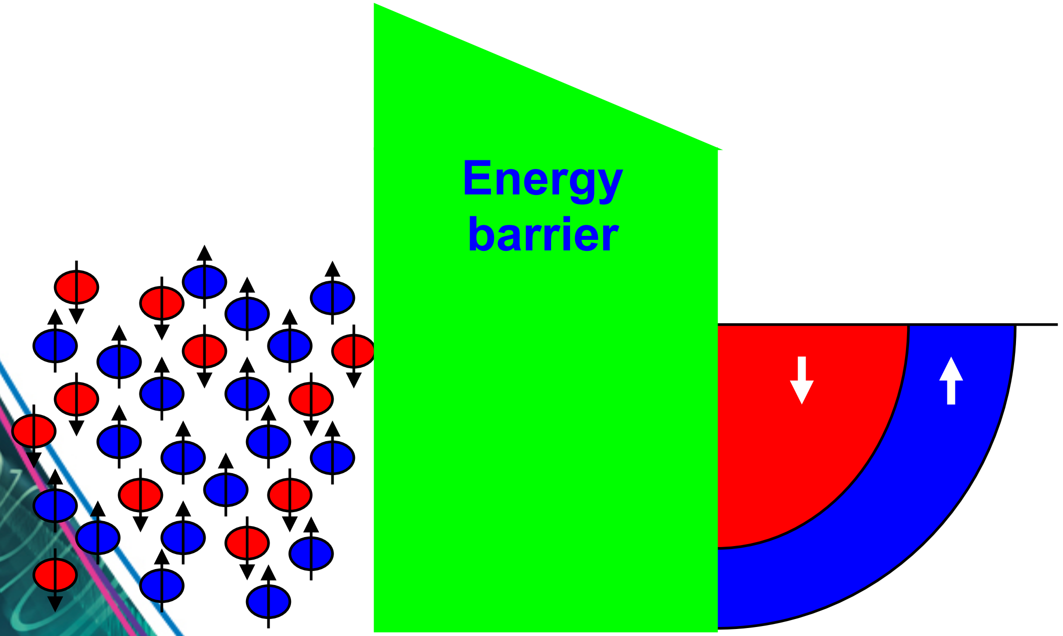
What is Tunnel Magnetoresistance (TMR)

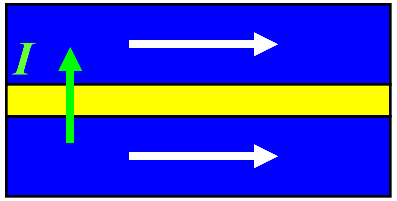
- spin dependent quantum transport across barriers -

GMR: **semi-classical physics**
- spin dependent scattering

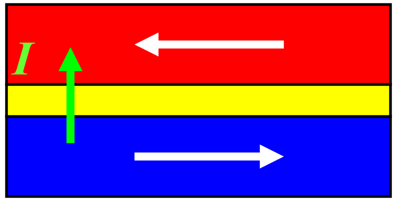
TMR: **quantum physics**
*- propagation of (**classically-forbidden**) evanescent waves*



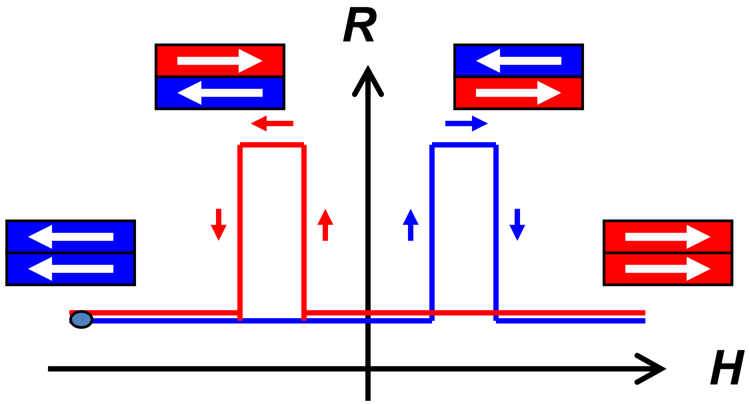




Low-R state



High-R state



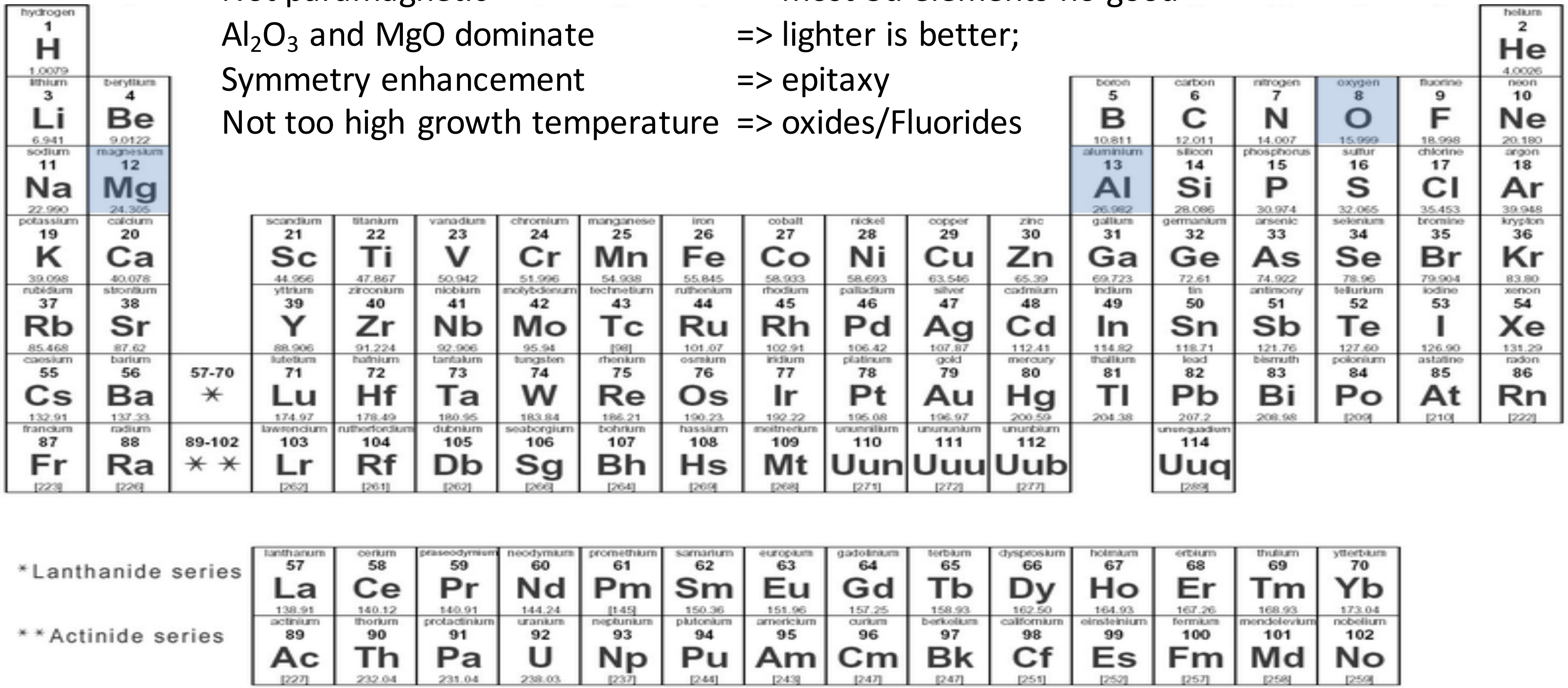
pseudo-spinvalve configuration

TMR = ΔR/R

What should we do beyond MgO?

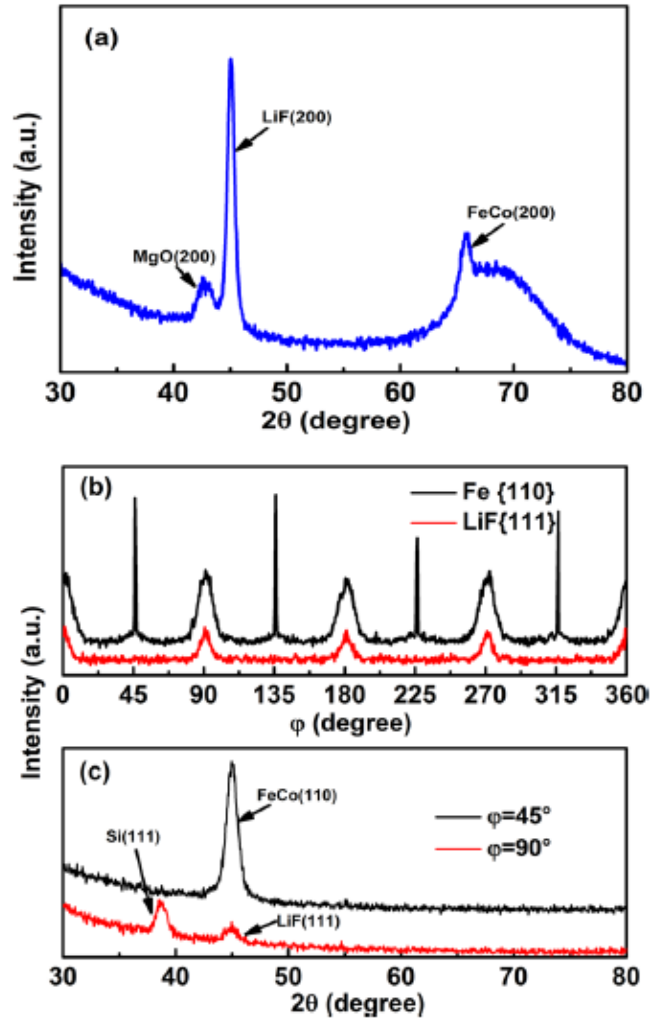
Design criteria:

- Not paramagnetic => most 3d elements no good
- Al_2O_3 and MgO dominate => lighter is better;
- Symmetry enhancement => epitaxy
- Not too high growth temperature => oxides/Fluorides



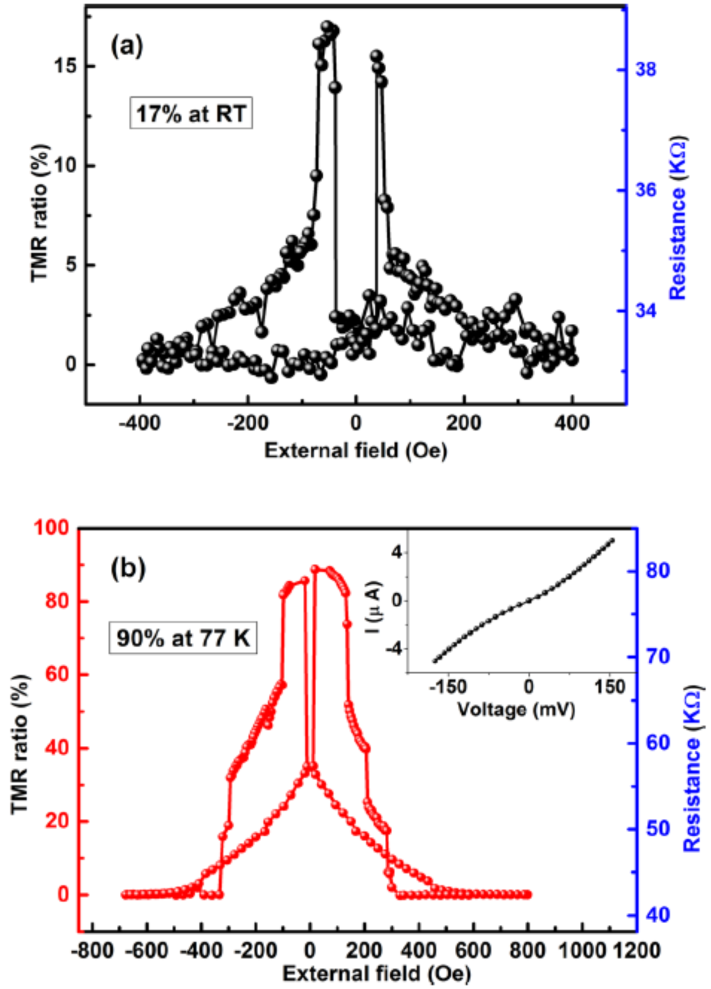
LiF?

(100)Si wafer/epi-MgO buffer/FeCo/LiF/FeCo



- MgO buffered Si(100) can readily seed bcc-FeCo or Fe growth;
- LiF easily epitaxial on the 3d bcc metals and alloys;
- Φ scan verifies 4-fold symmetry, as expected for epitaxy;

Comparable to the early stage of MgO devices;
(UHV? Post annealing? Nano fabrication?)



Acknowledgement

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Prof. Kui-Juan Jin & Hai-Zhong Guo, Li-Cong Peng, Lin Gu (Chinese Institute of Physics)

TQT Transformative Quantum Technologies

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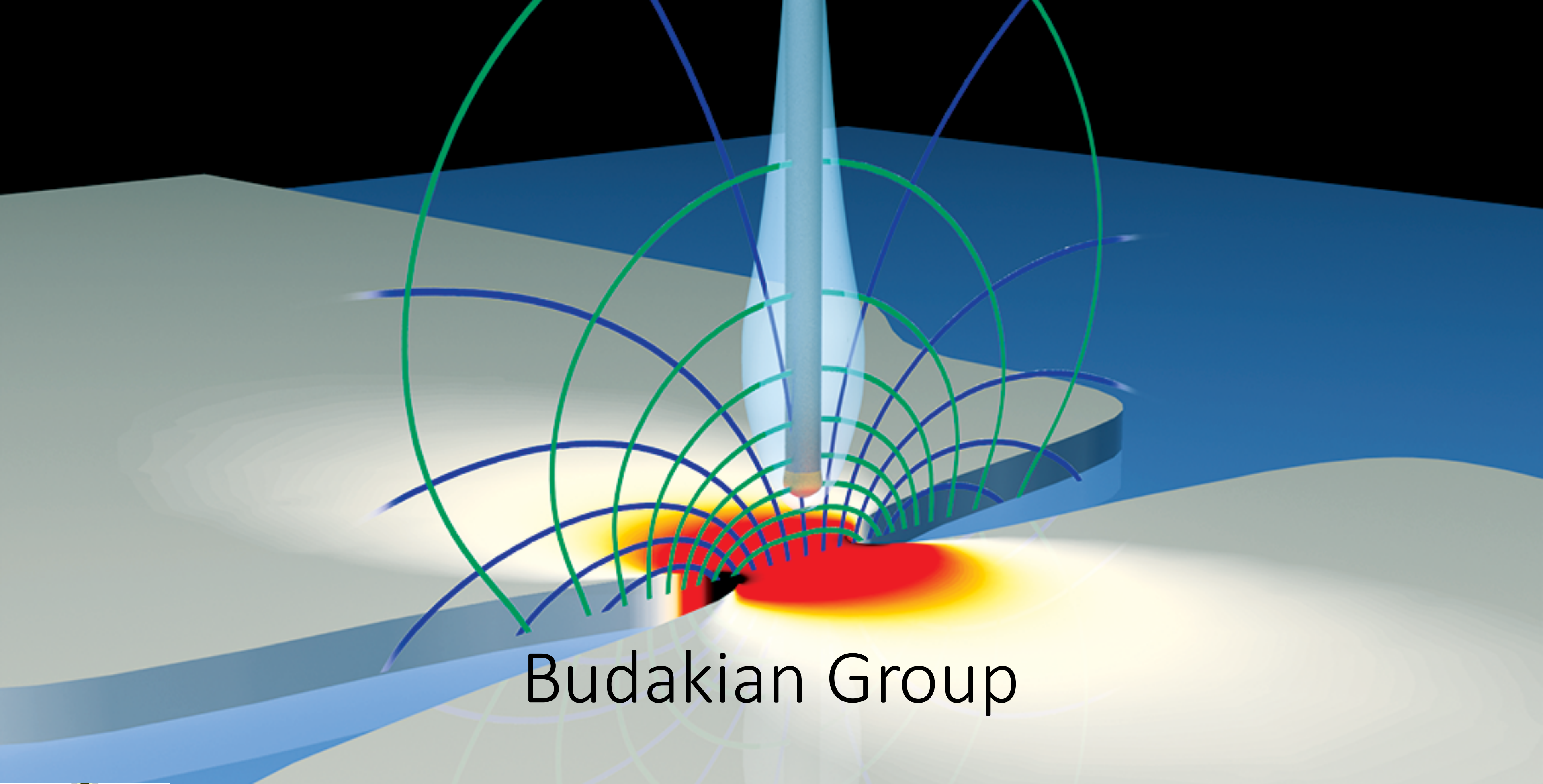
Ontario

High Resolution Nanoscale Magnetic Resonance Imaging and Spectroscopy



Budakian Group

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Grand Challenge—Protein Structure Determination

- Membrane proteins comprise 25-30% of proteins in all living species, and 40-60% of drug targets.
- Understanding the structure and dynamics of proteins is vital to determining their function.
- X-ray crystallography is the most widely used technique for determining protein structure, with over 90% of the structures in the protein database (PDB) being solved using this technique.
- X-ray crystallography has shown limited success—of more than 100,000 entries in the PDB, only 600 of these are unique protein membrane entries.
- New approaches to protein structure determination would significantly advance drug development.

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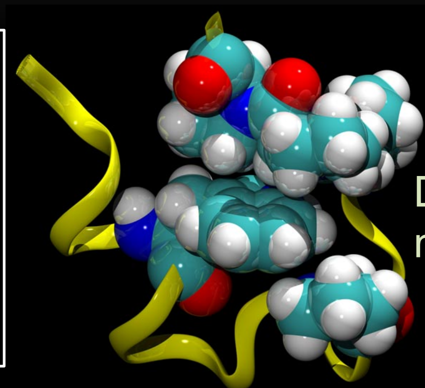
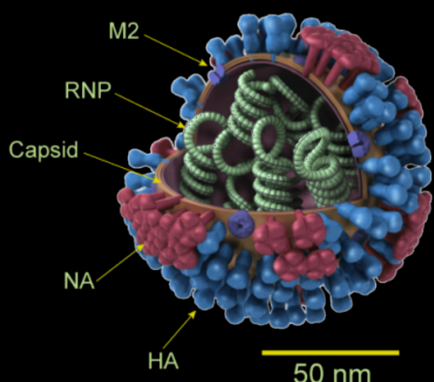
Nanometer-scale magnetic resonance imaging (Nano-MRI) would extend the three-dimensional imaging capability of MRI to the nanometer scale, and provide fundamentally new ways to image biological systems.

Combined with the ability to image materials non-destructively and with chemical specificity, this capability would enable structure determination of single biomolecules and virus particles.



Direct determination of molecular structure



Three dimensional tomography of single virus particles with elemental selectivity

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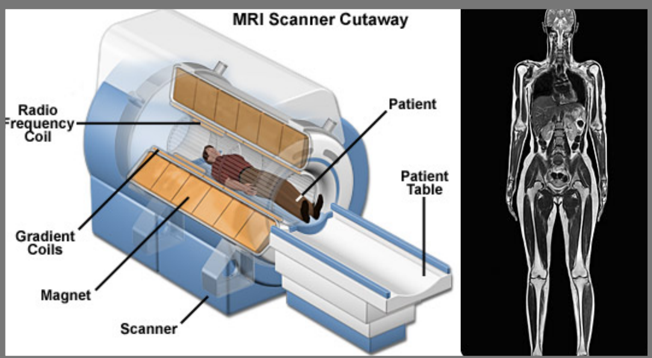
MRI Technology

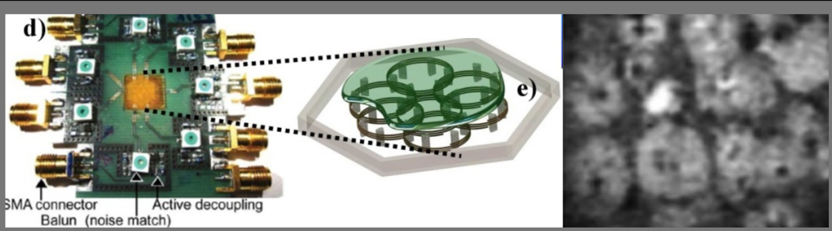
10 μm– 0.1 nm
70 ^{1}H/nm^{3}

Clinical



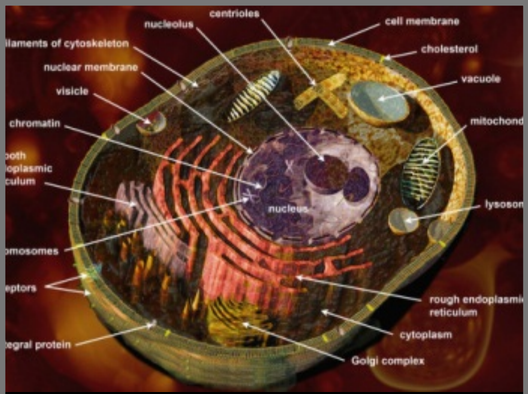
1 m – 1 mm
7×10^{19} ^{1}H/mm^{3}

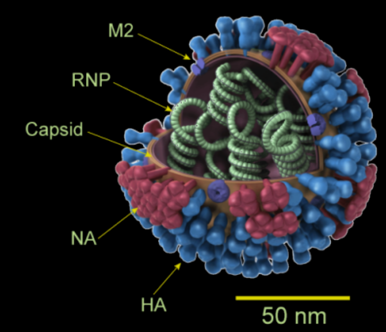
Microcoil MRI

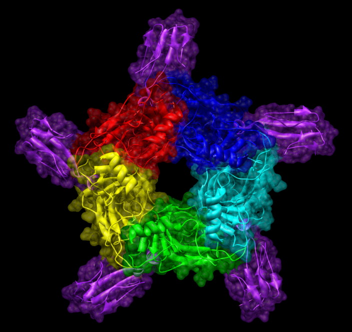


1 mm ~ 3 μm
7×10^{10} ^{1}H/(1 μm)^{3}

?







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Develop a nanoMRI platform that combines

- The ability to detect nanoscale ensembles of nuclear spins and single electron spins.
- Intense magnetic fields for high-fidelity quantum control
- Intense magnetic field gradients for nanometer scale magnetic resonance imaging.

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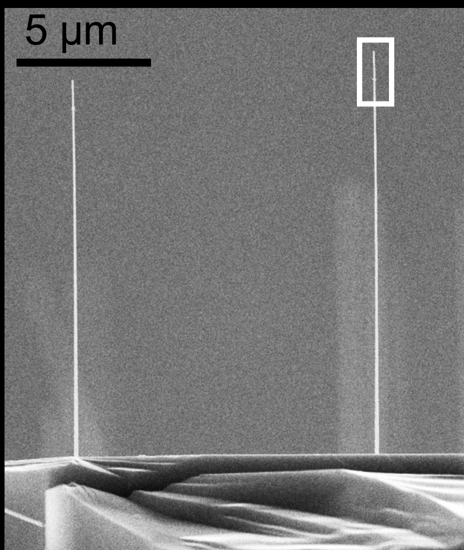
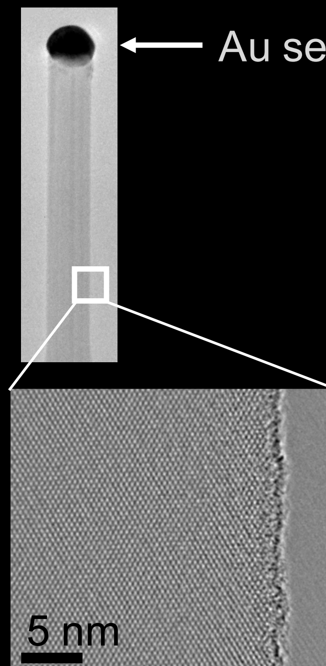
Force-Detected MRI

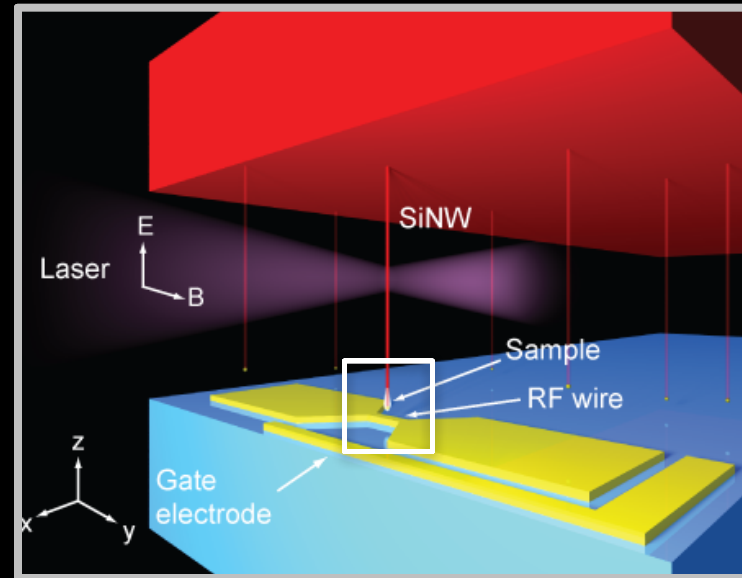
Silicon nanowire resonator

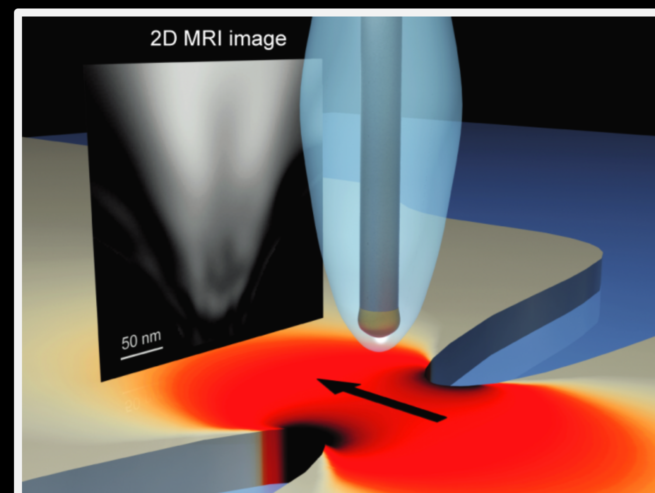


50-100 nm diameter



At 4K, force sensitivity ~ 1 aN = 10^{-18} N





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High-Resolution Nanoscale Solid-State Nuclear Magnetic Resonance Spectroscopy

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Lincoln J. Lauhon,[4] David G. Cory,[3,5,6,7] and Raffi Budakian[1,2,3,6,7,†]

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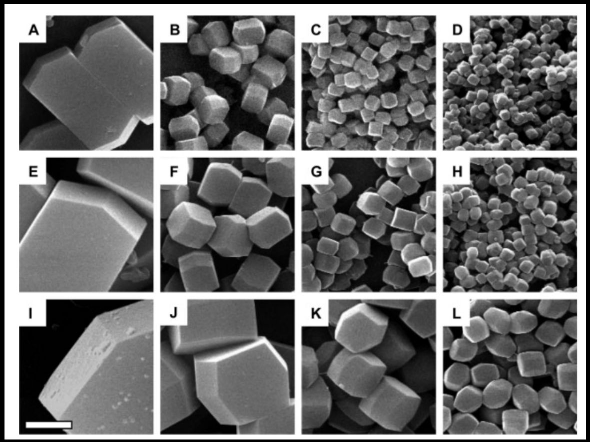
[7]*Canadian Institute for Advanced Research, Toronto, ON, Canada, M5G1Z8*

We present a new method for high-resolution nanoscale magnetic resonance imaging (nano-MRI) that combines the high spin sensitivity of nanowire-based magnetic resonance detection with high spectral resolution nuclear magnetic resonance (NMR) spectroscopy. By applying NMR pulses designed using optimal control theory, we demonstrate a factor of 500 reduction of the proton spin resonance linewidth in a $(50\text{-nm})^3$ volume of polystyrene, and image proton spins in one dimension with a spatial resolution below 2 nm.

arXiv:1707.01062

Nuclear Magnetic Resonance Diffraction (patent pending)

- Coherent NMR diffraction from a lattice of spins—atomic scale information can be obtained without the need to detect individual spins.



- Many proteins, e.g. membrane proteins, can be synthesized as nanocyrstals.

- NMR diffraction measurements of protein nanocrystals can augment X-ray scattering data by providing Angstrom scale, spin specific protein structure.

- Key requirements for atomic scale NMR diffraction:
  - High field gradients (~ 10^6 T/m)
  - Long coherence times (~ 100 μs)
  - High-fidelity spin control