Quantum Applications Build on Creative Nanofabrication

Tony X. Zhou

zhou01@mit.edu

Post-doc with Prof. Karl Berggren

Massachusetts Institute of Technology

Formerly at Harvard with Prof. Amir Yacoby

gztony1227@gmail.com

4/22/2022 for NNCI Etch Symposium

My favorite materials for Quantum Applications

Superconductors

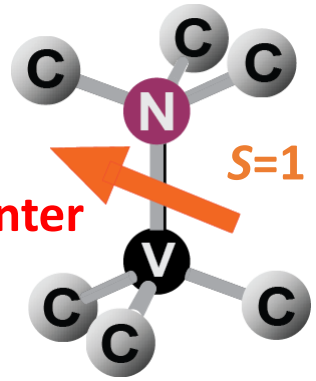
Photo:
https://www.extremetech.com/

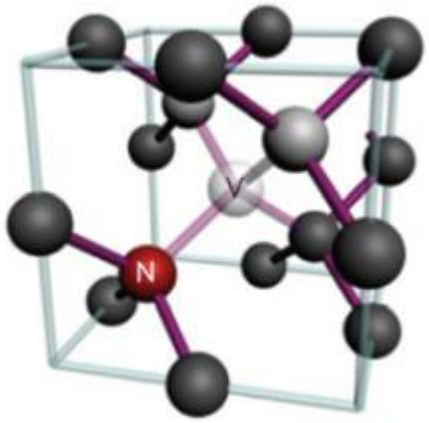
Diamonds

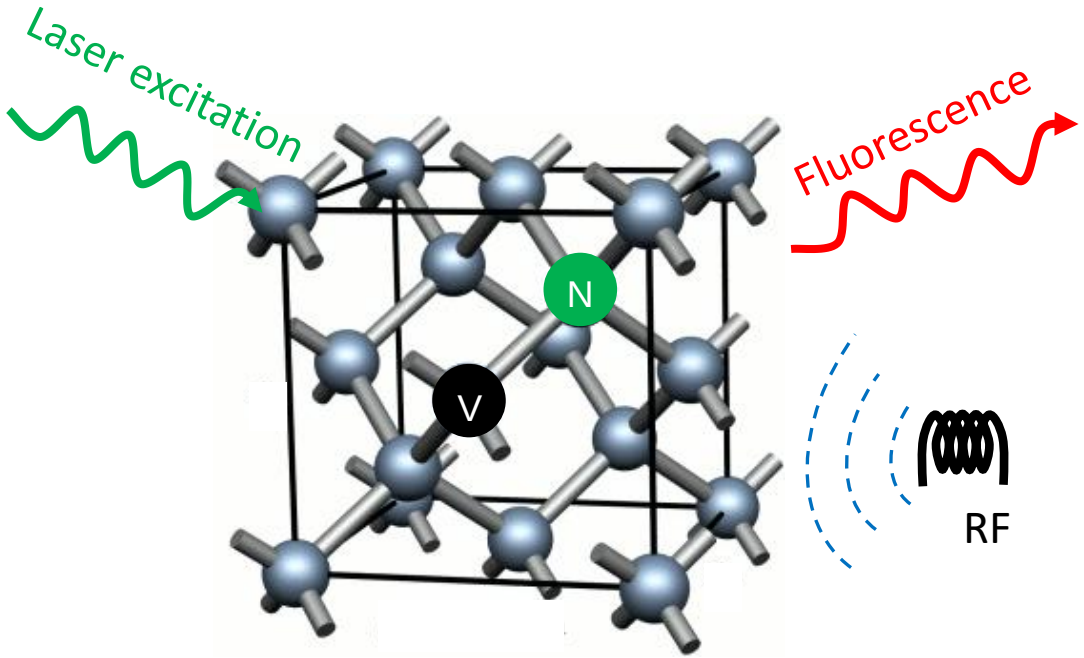
Photo:
https://www.pinterest.com/pin/675610381577582322/

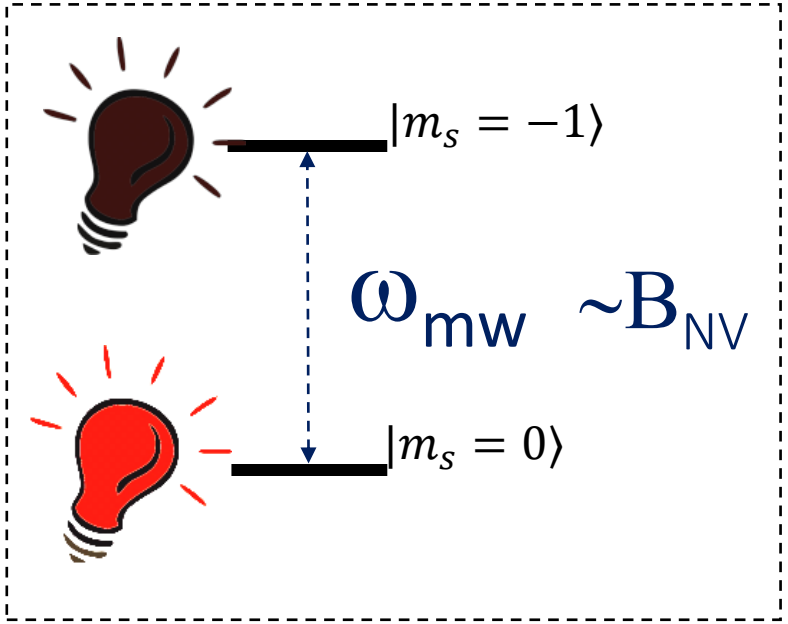
NV center in diamond, a spin qubit as magnetometer

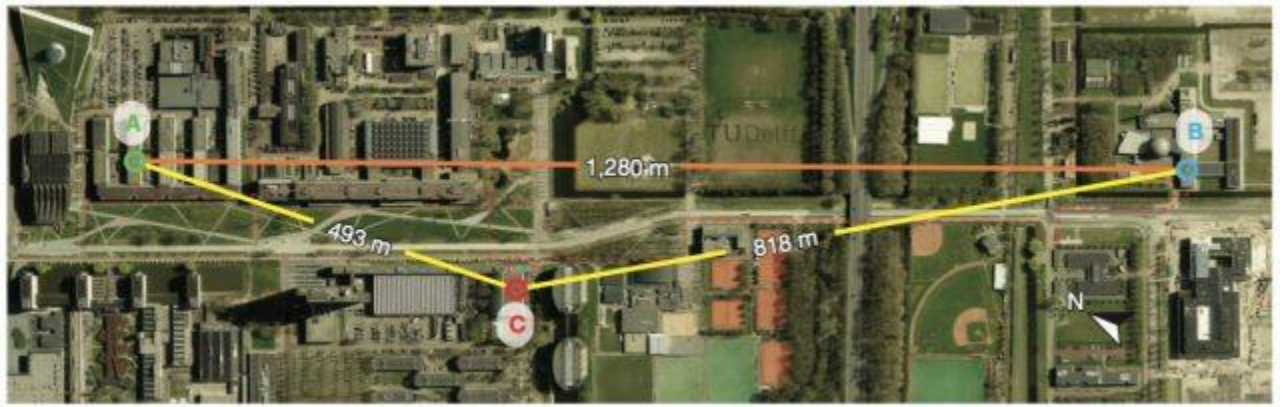
Nitrogen
Vacancy center
in diamond












The New York Times

Assad Finds Chilly Embrace In Moscow Trip

Putin Is Syrian's Ally, but No Close Friend

BIDEN CONCLUDES THERE'S NO TIME FOR A 2016 RUN

PATH EASES FOR CLINTON

Pope's Plans for Inclusiveness Divide Bishops

Debating the Place of Divorced or Gay Catholics

Caucus Clears Path for Ryan To Be Speaker

Airbag Study Was Kept Quiet During Recalls

Officer Faced a Man on the Run

Sorry, Einstein, but 'Spooky Action' Seems Real

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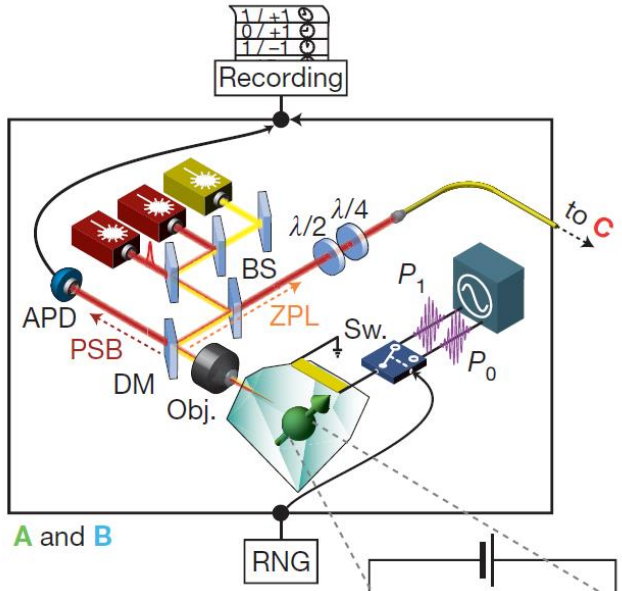
Archive | Volume 526 | Issue 7575 | Letters | Article

NATURE | LETTER

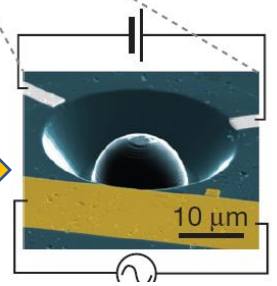
日本語要約

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau & R. Hanson

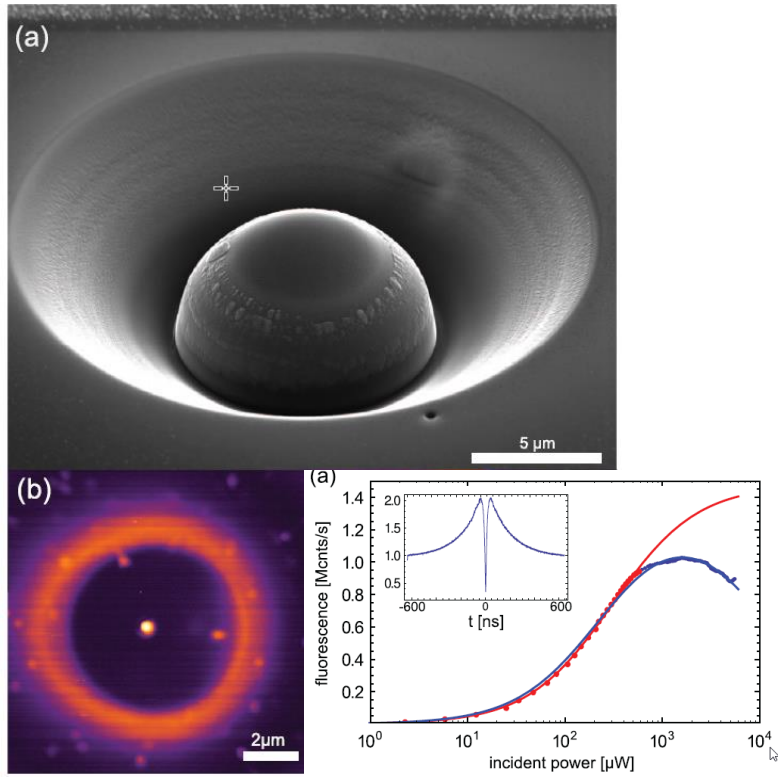


Impossible without this



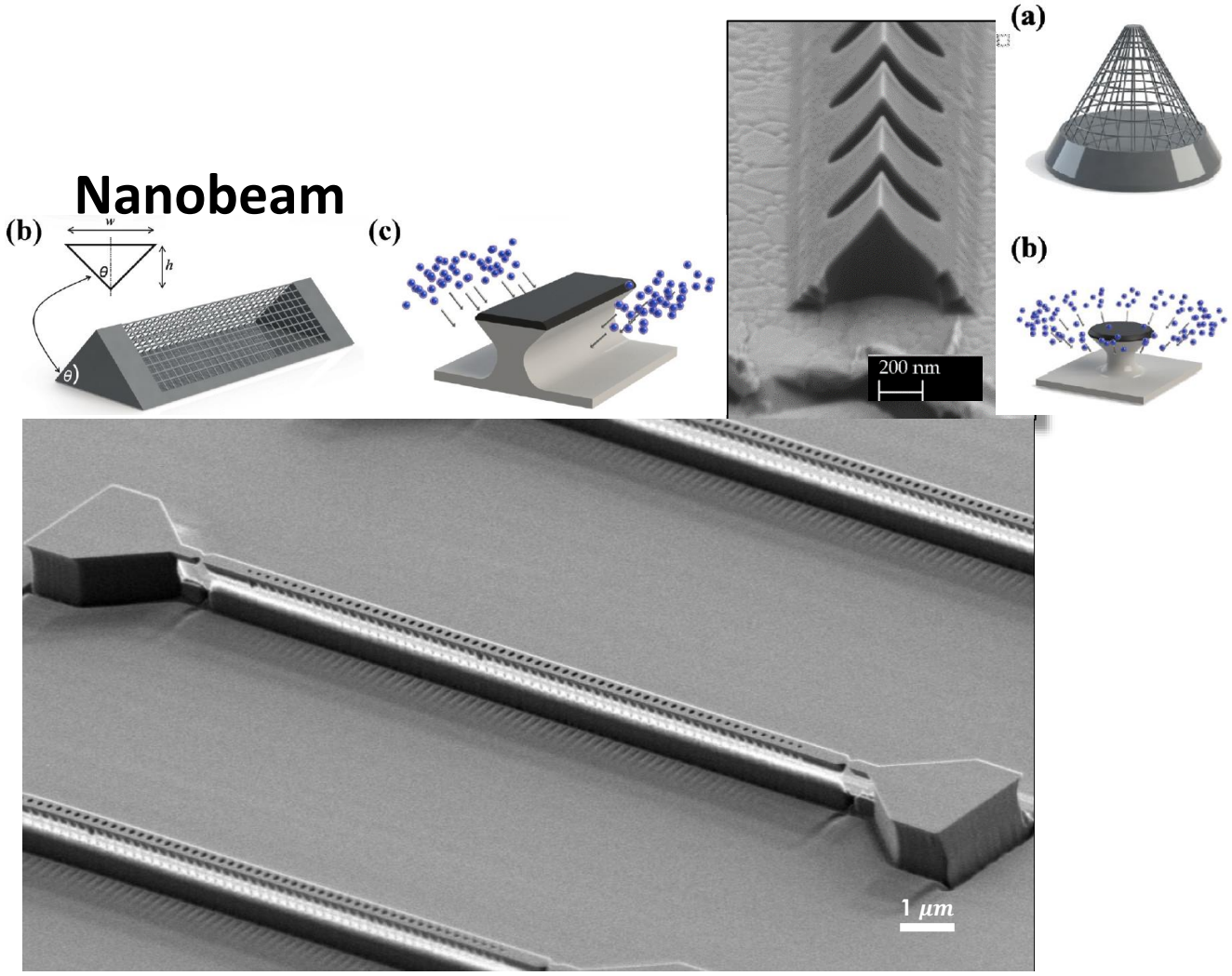
Most important process is the etch

Solid Immersion Lens (SIL)



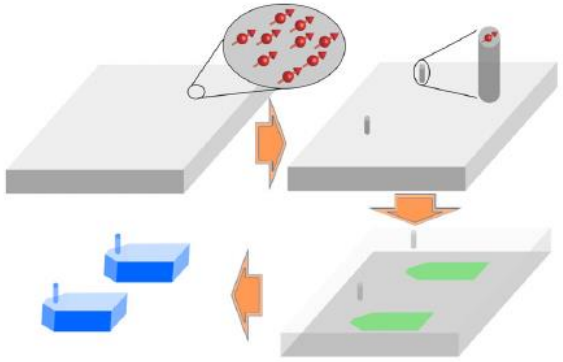
M. Jamali *et al.*, *Review of Scientific Instruments*. **85**, 123703 (2014).

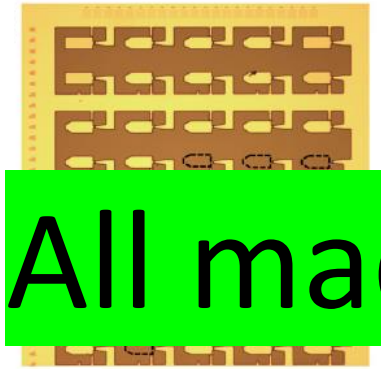
Nanobeam

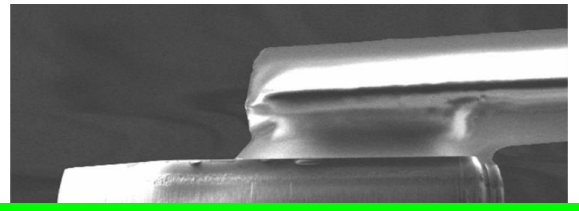


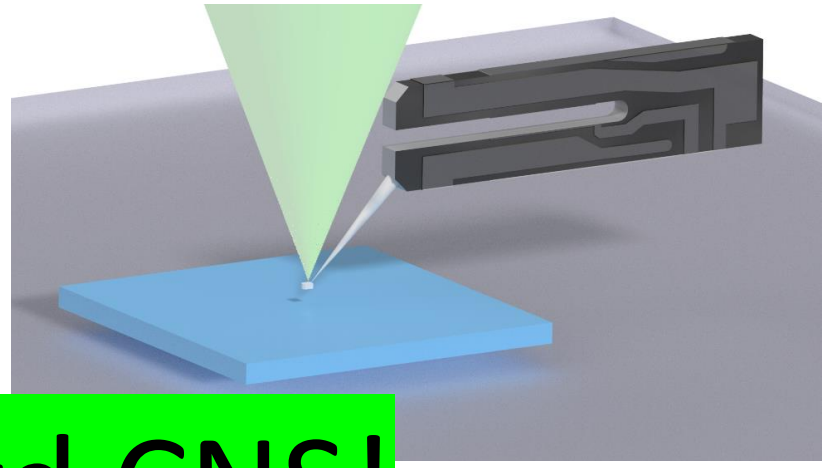
M.J. Burek, Nature Comm., 5, 5718 (2014)

My etch work-making scanning probes

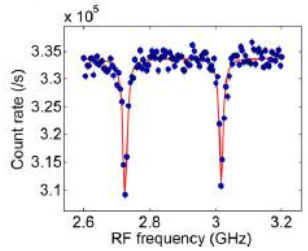


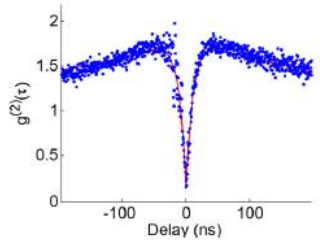


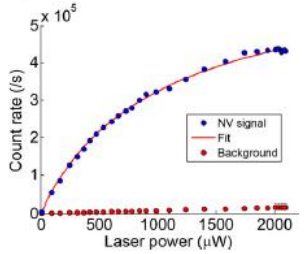


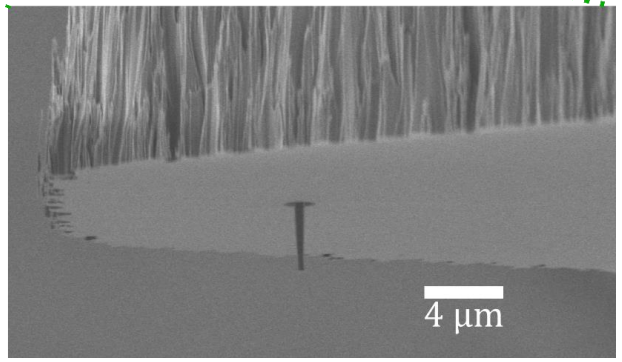


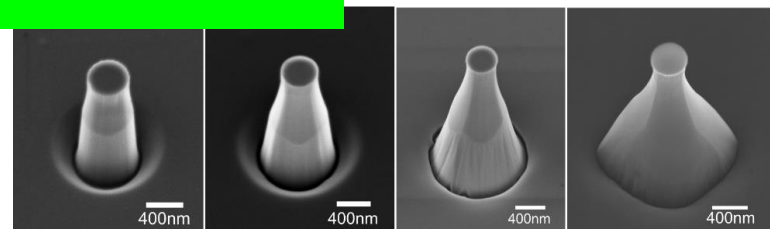
All made in Harvard CNS!











Tony X. Zhou*, R. J. S*, A. Y, *Appl. Phys. Lett.* **111**, 163106 (2017). (*equal contribution)

L. X*, **Tony X. Zhou***, R. J. S, A. Y, *Advanced Materials*. **30**, 1705501 (2018). (*equal contribution)

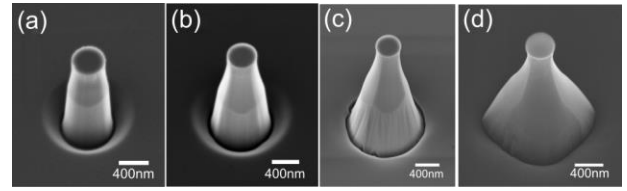
COMMUNICATION

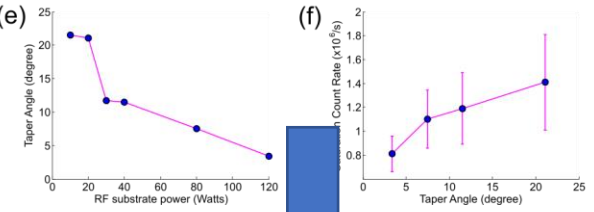
Ion Etching

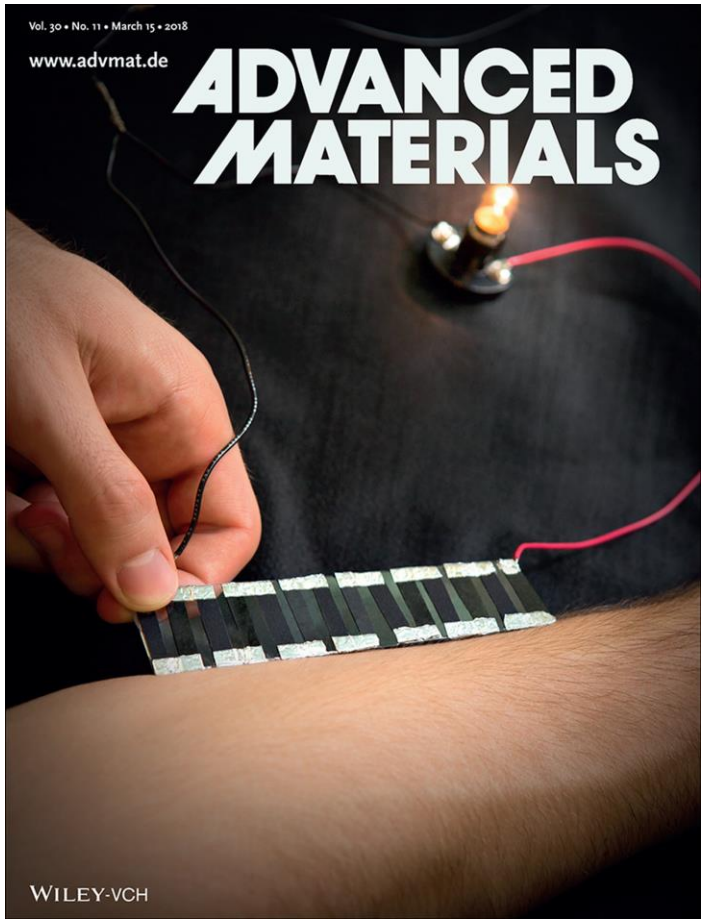
ADVANCED MATERIALS
www.advmat.de

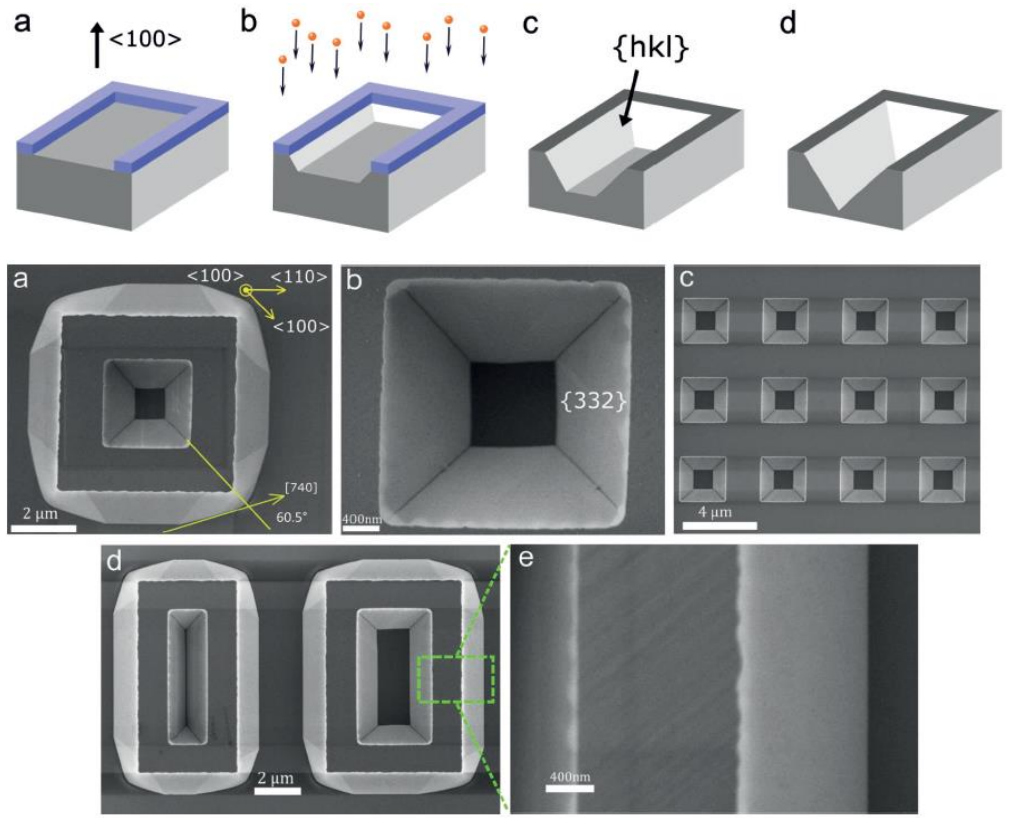
Crystallographic Orientation Dependent Reactive Ion Etching in Single Crystal Diamond

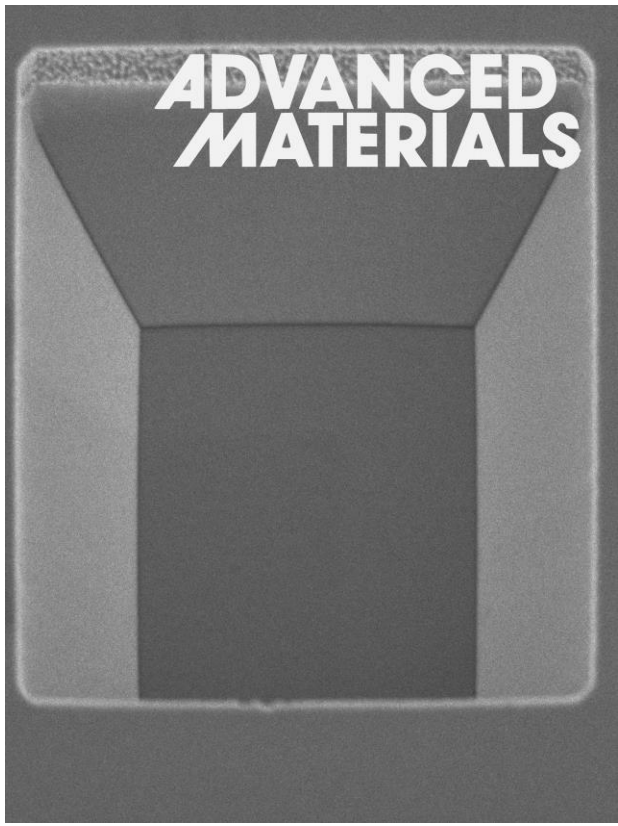
*Ling Xie, Tony X. Zhou, Rainer J. Stöhr, and Amir Yacoby**





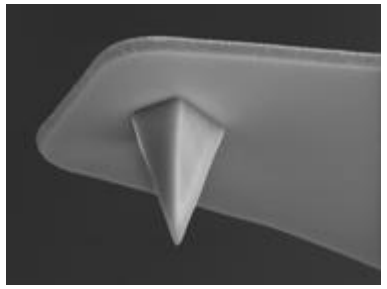


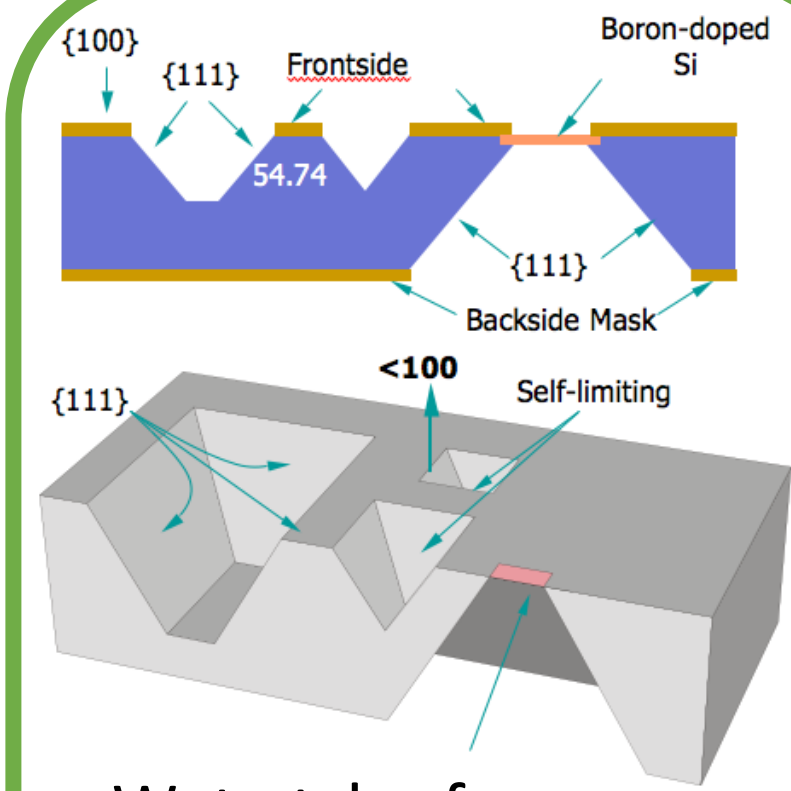




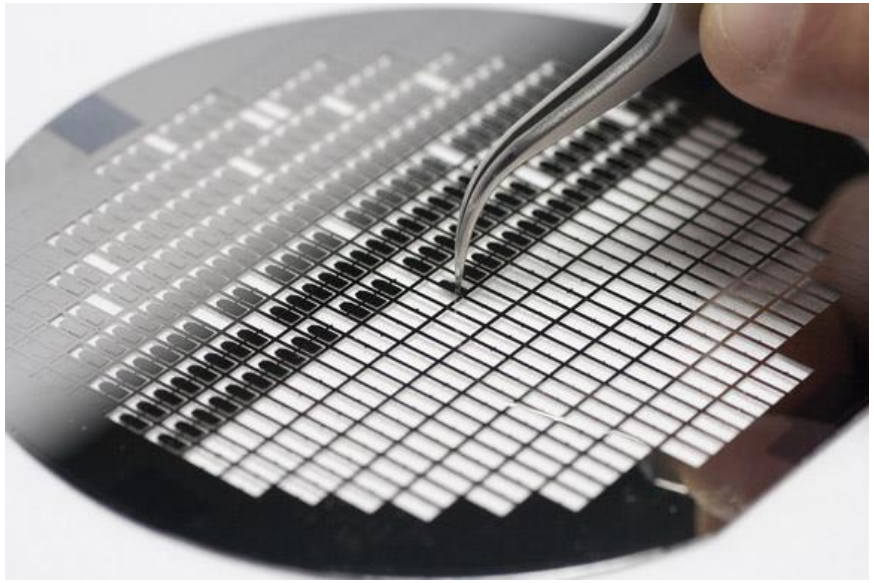
Advanced Materials. **30**, 1705501 (2018)

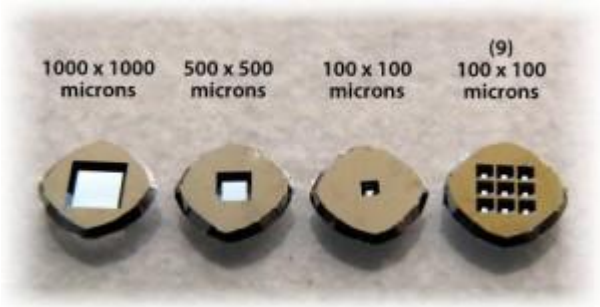
Silicon fabrication





Wet etch of silicon in KOH

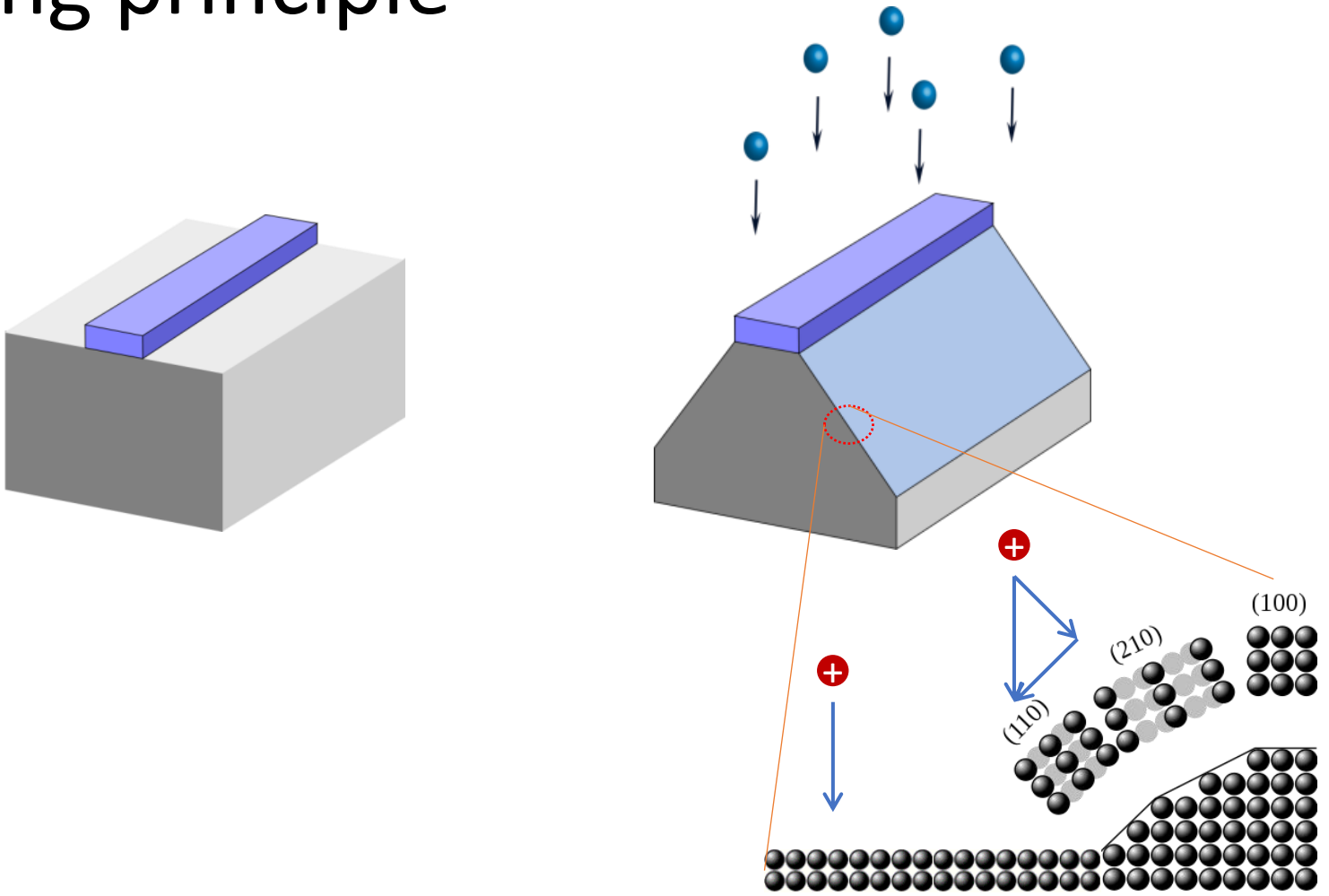




Images from Asylum and Bruker websites

Image from https://www.mems-exchange.org/

Etching principle

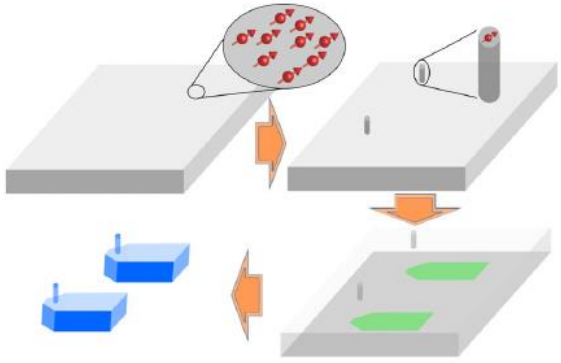


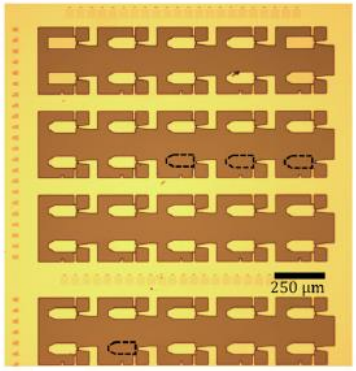
Independently tune the ion energy close to energies required to etch crystal planes

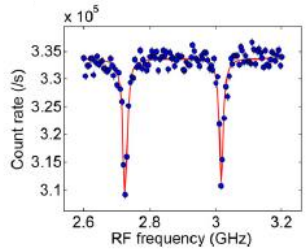
It should happen in all crystalline materials

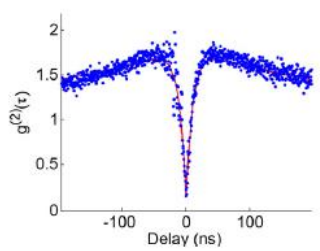
Image from https://themoonlightshop.com

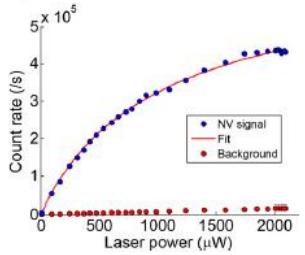
A single NV center as a scanning probe microscopy sensor

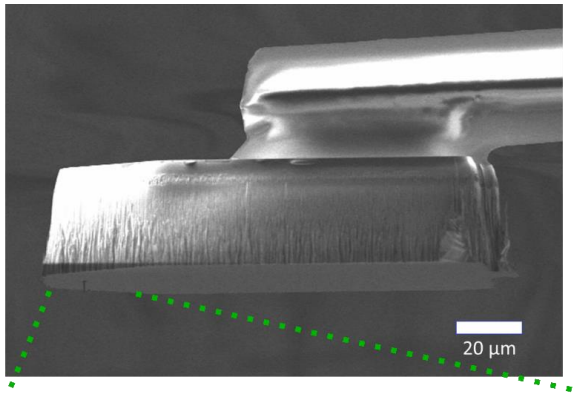


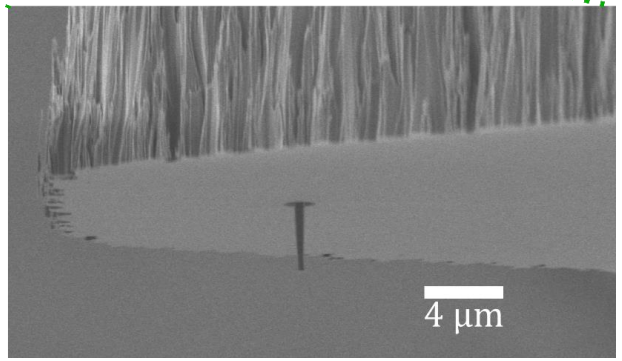


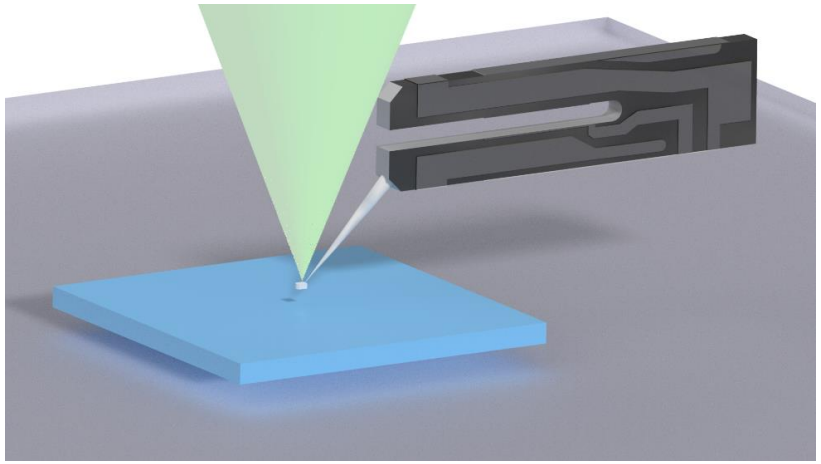


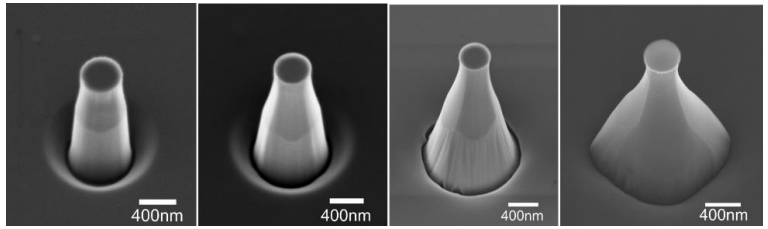










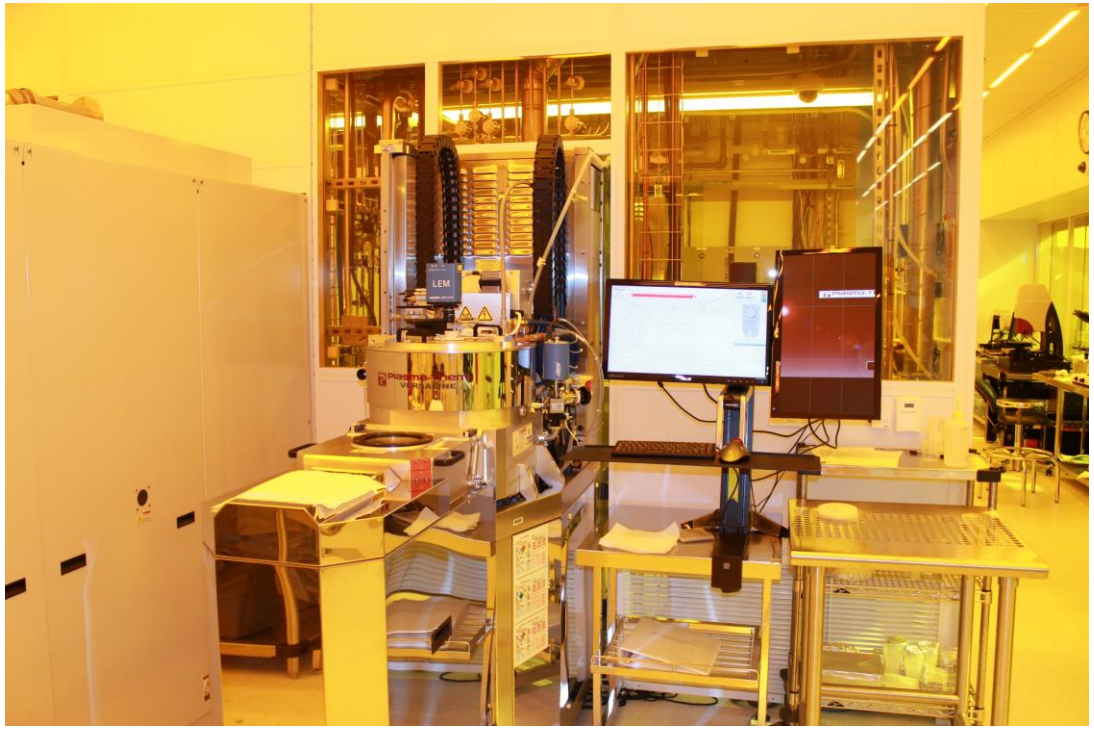


Tony X. Zhou*, R. J. S*, A. Y, *Appl. Phys. Lett.* **111**, 163106 (2017). (*equal contribution)

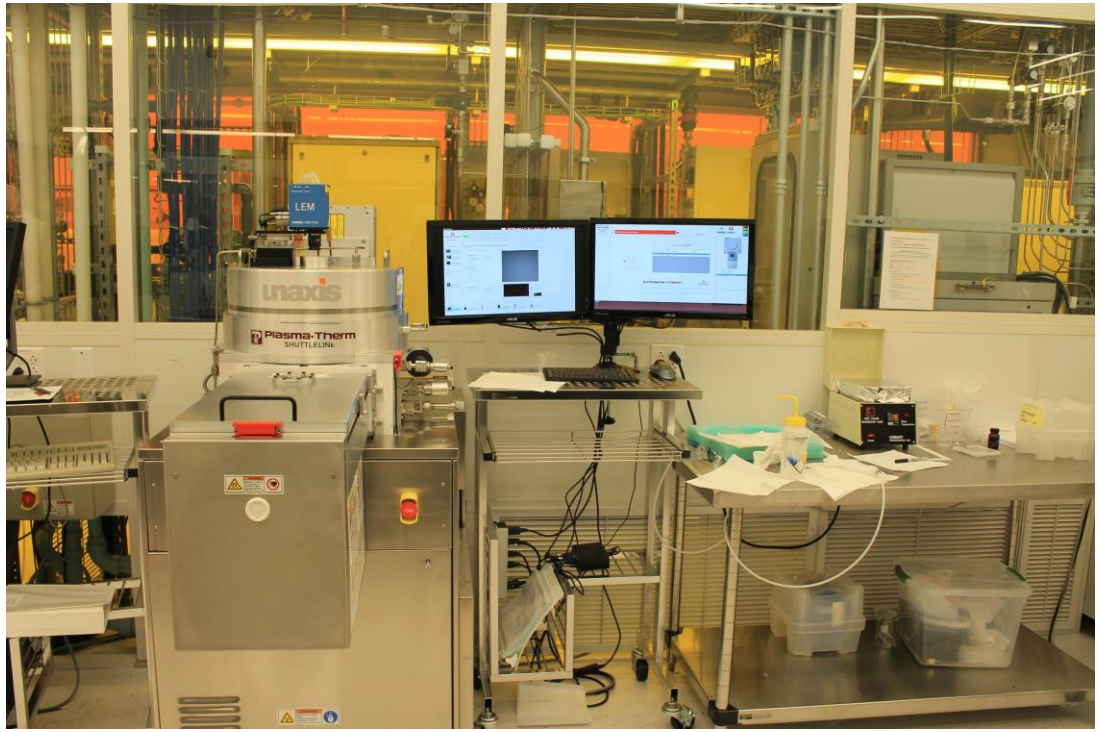
L. X*, **Tony X. Zhou***, R. J. S, A. Y, *Advanced Materials*. **30**, 1705501 (2018). (*equal contribution)

Workhorse

Plasma-Therm Versaline



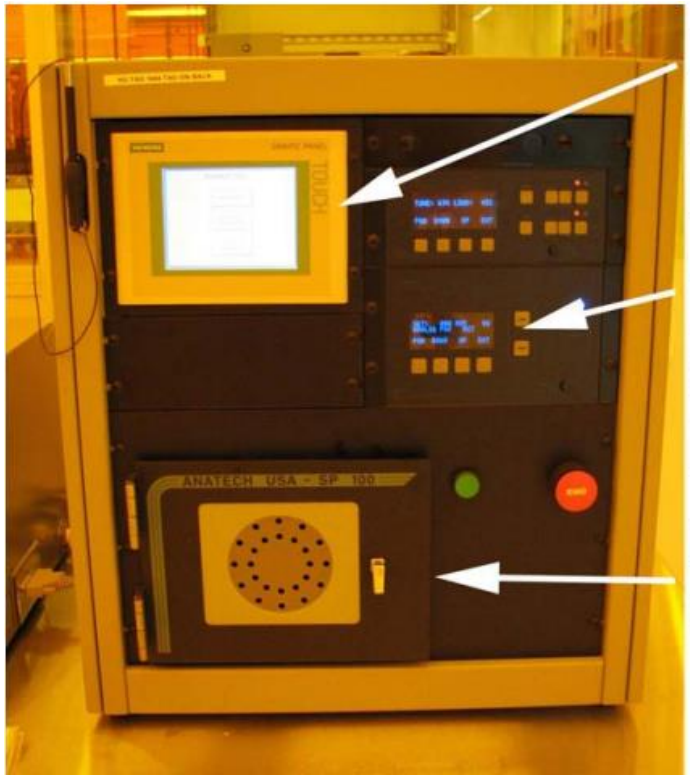
Unaxis Shuttleline ICP



Important support cast

SouthBay 2000

Anatech Barrel SCE 106

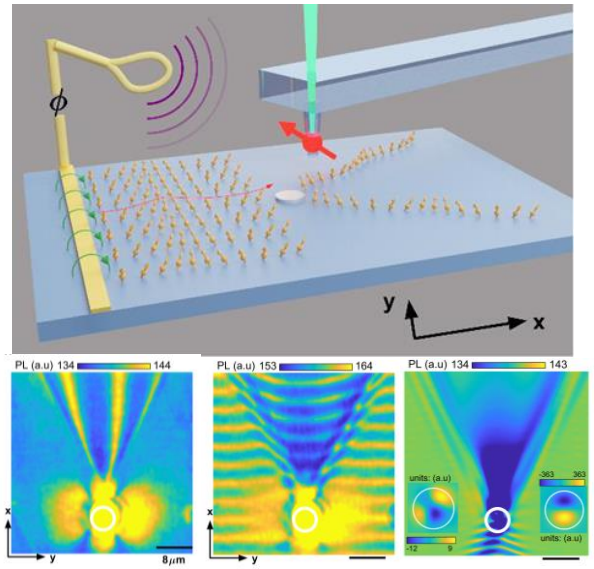


Quantum Sensing

"By using a quantum sensor as a magnetometer, we explore many scientific fronts"

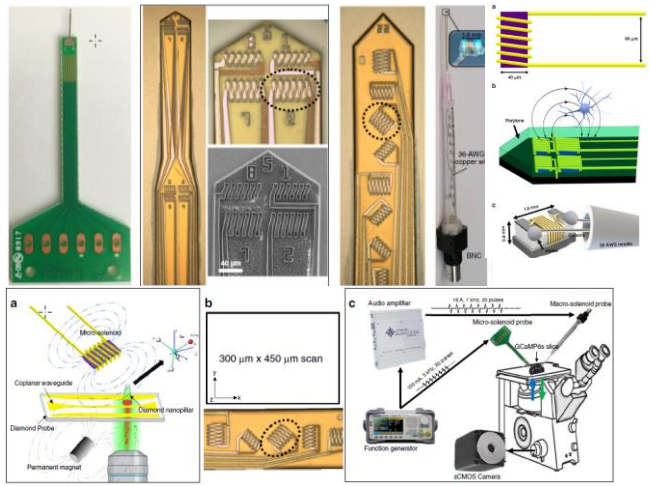
Tony

Study Magnon Scattering



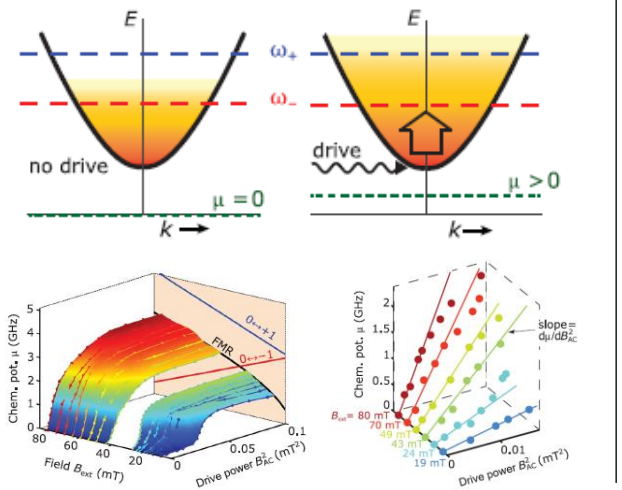
Tony X. Zhou *et al.*, "A magnon scattering platform," *PNAS*, 118, 25, Jun. 2021

Study Neuron Excitation Coils



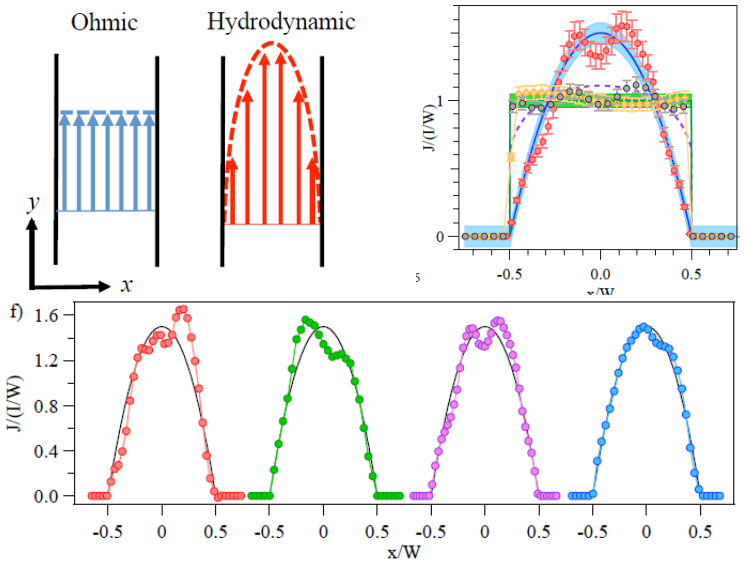
A. Khalifa*, M. Zaeimbashi*, **Tony X. Zhou**, S. M. Abrishami, N. Sun, et al, *Microsystems & Nanoengineering*. 7, 1 (Nov. 2021), 1–10. (*equal contribution)

Study Magnons



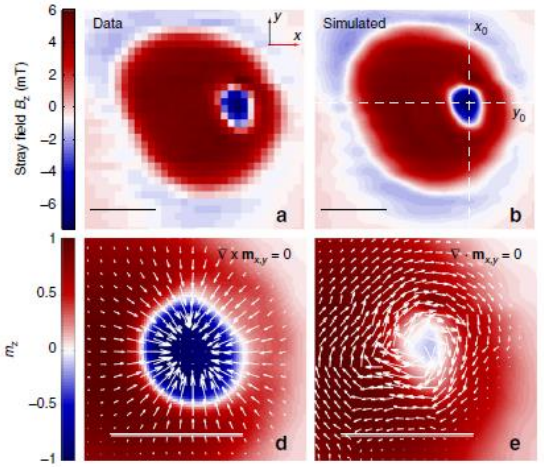
C. Du*, T. van der Sar*, **Tony X. Zhou*** et al, Science. 357, 195–198 (2017). (*equal contribution)

Study Hydrodynamics



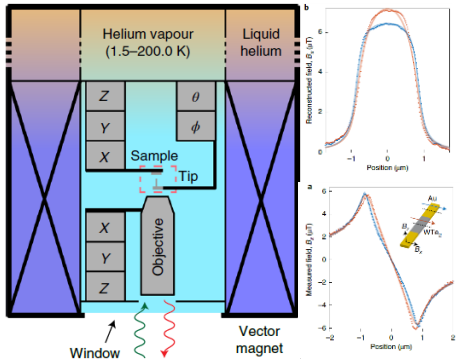
M. J. H. Ku*, **Tony X. Zhou***, *et al.*, *Nature*. **583**, 537–541 (2020). (*equal contribution)

Study Skyrmion



Y. Dovzhenko*, F. Casola*, S. Schlotter, **Tony X. Zhou** *et al, Nature Communications*. **9**, 2712 (2018). (*equal contribution)

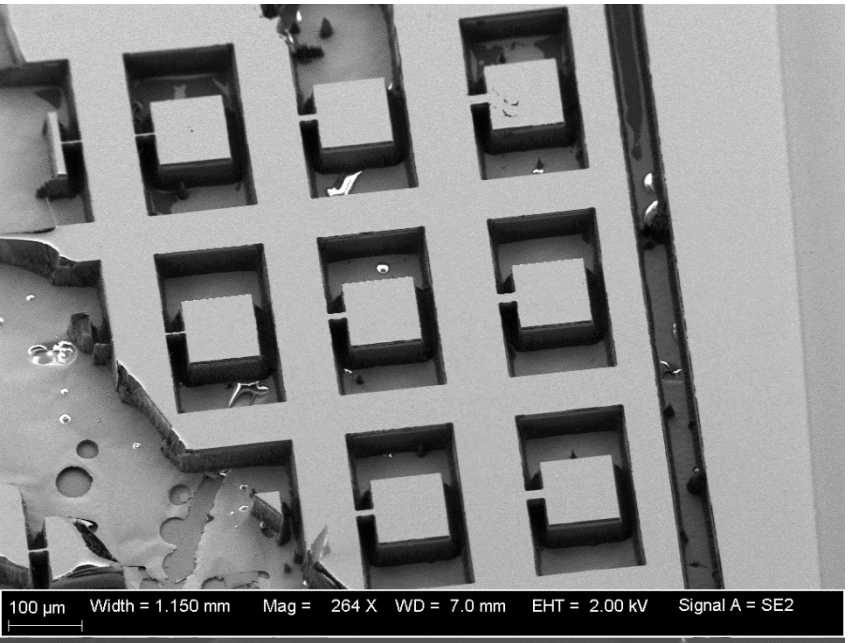
Study Semi-metal

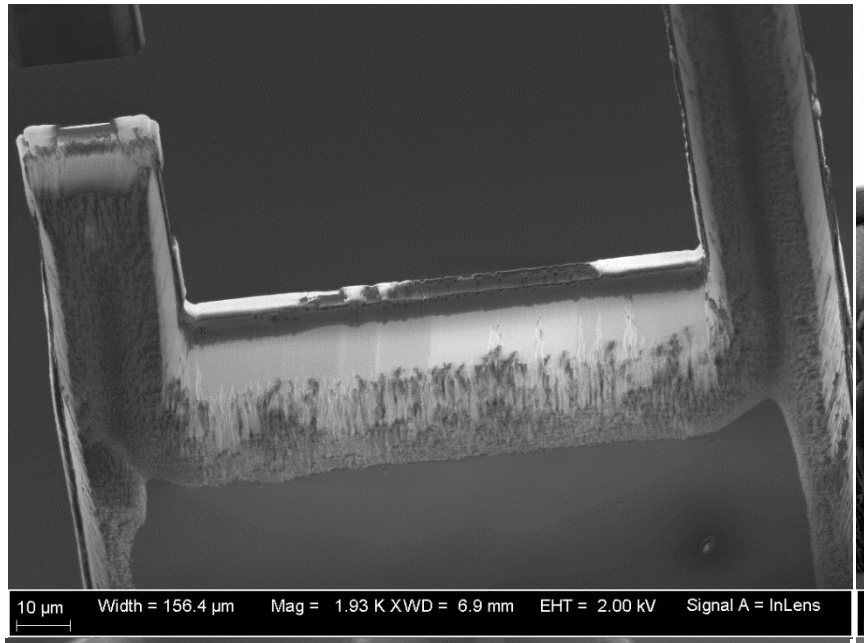


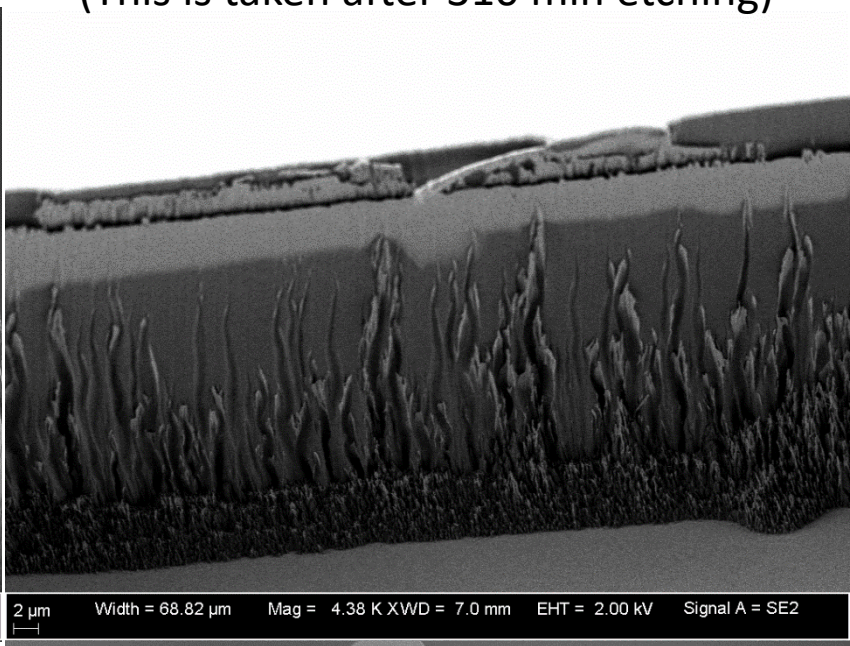
U. Vool*, A. Hamo*, G. Varnavides*, Y. Wang*, **Tony X. Zhou** , *et al.*, *Nature. Physics.*, pp. 1–5, (2021). (*equal contribution)

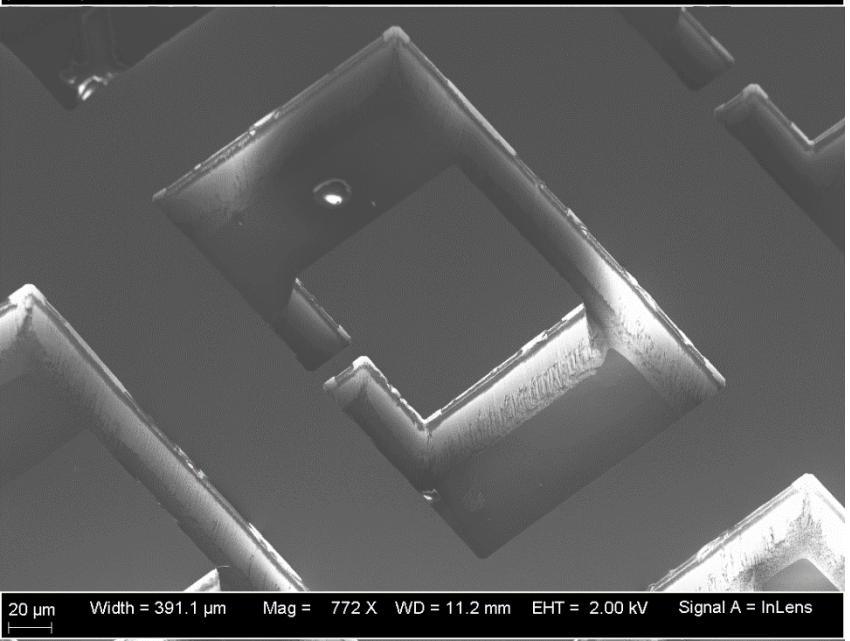
Lots of open questions still left in diamond etching

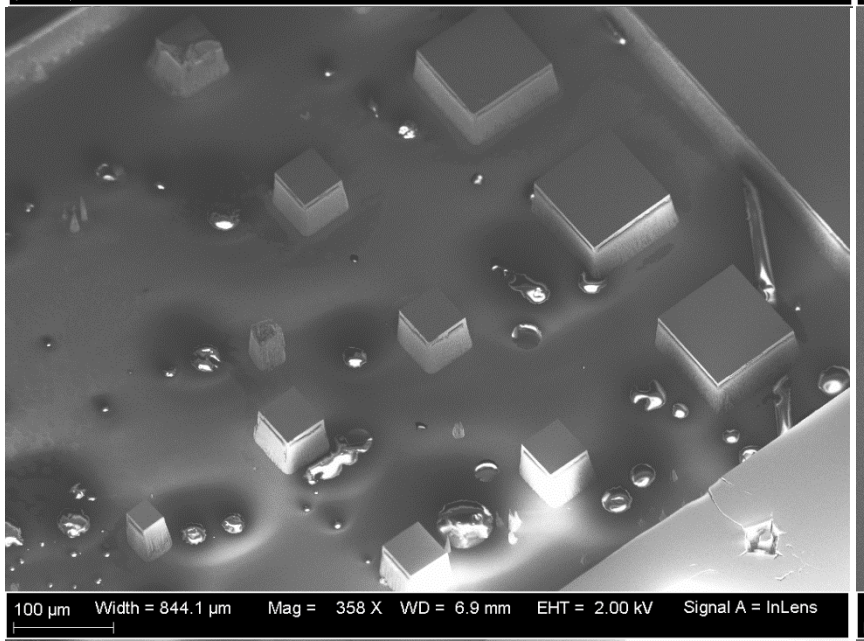
Narrow trenches might not be etched all the way through !
(This is taken after 310 min etching)

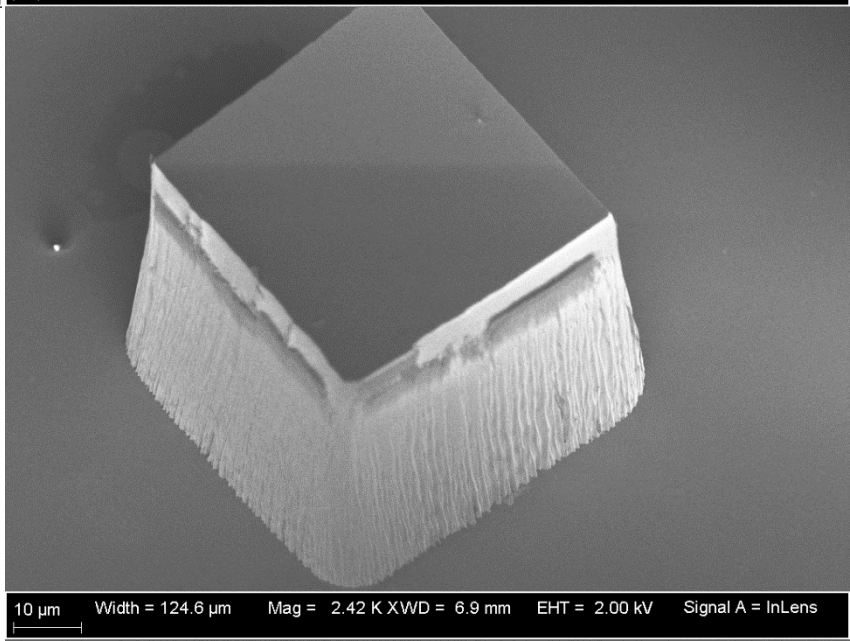




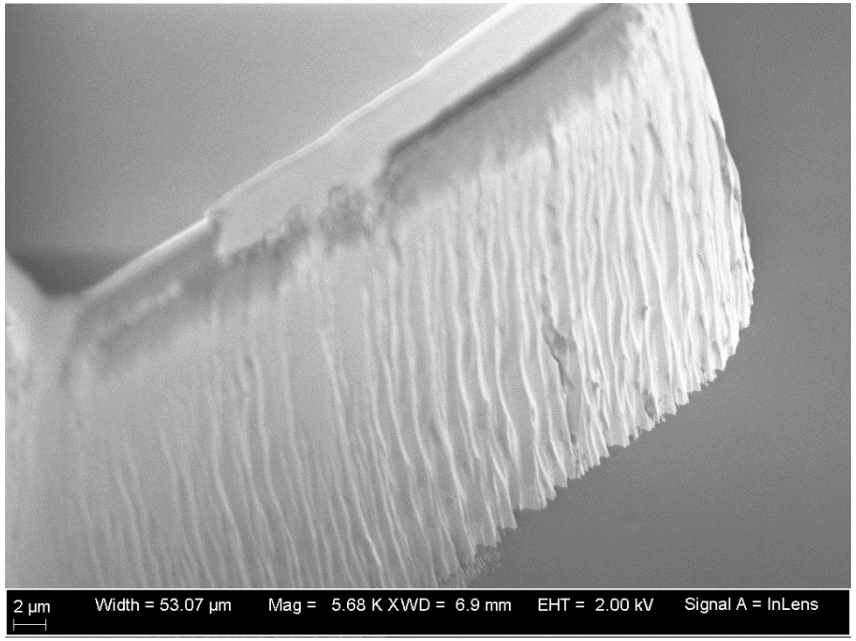


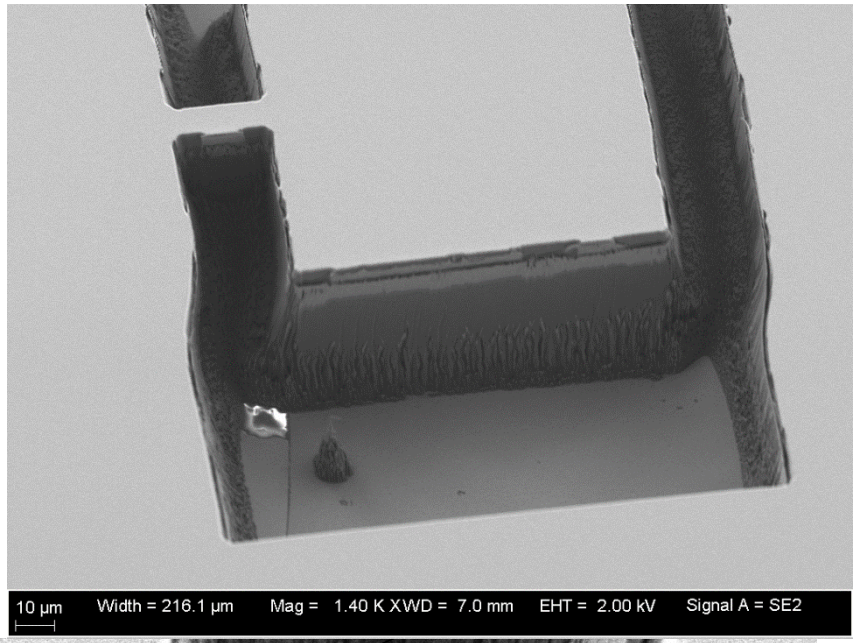


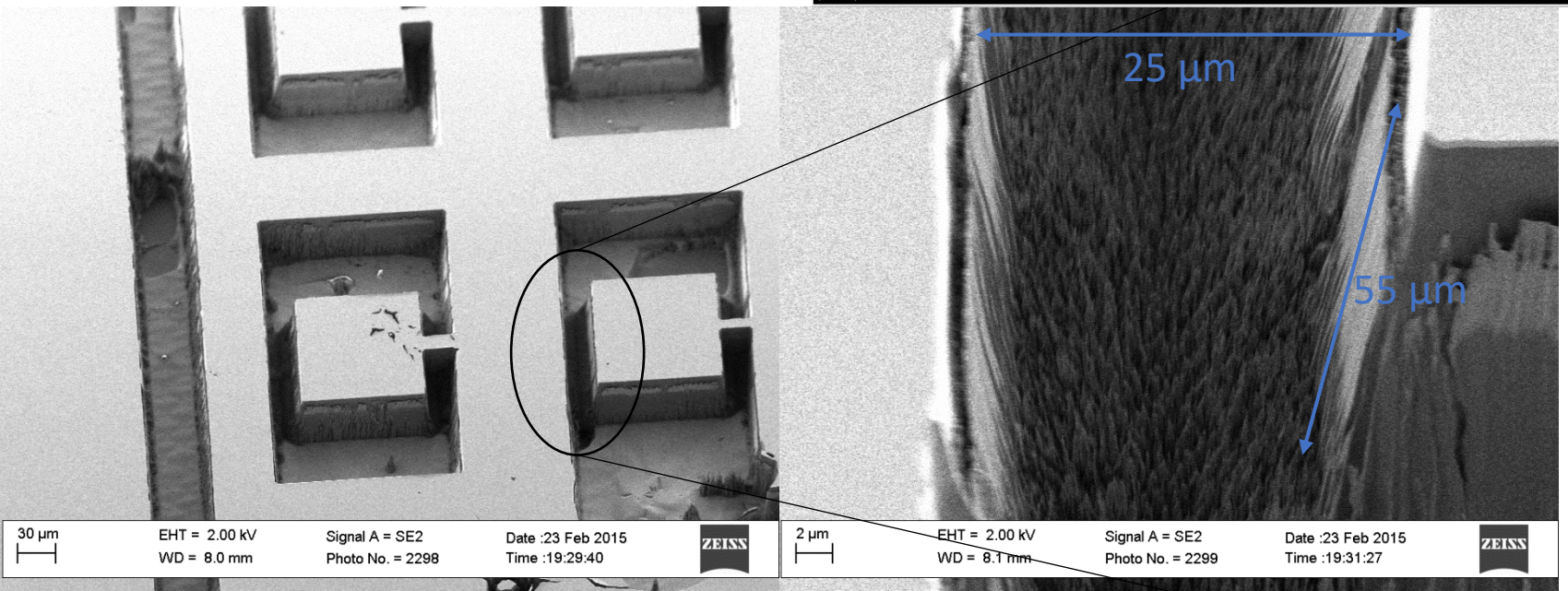




Lots of open questions still left in diamond etching

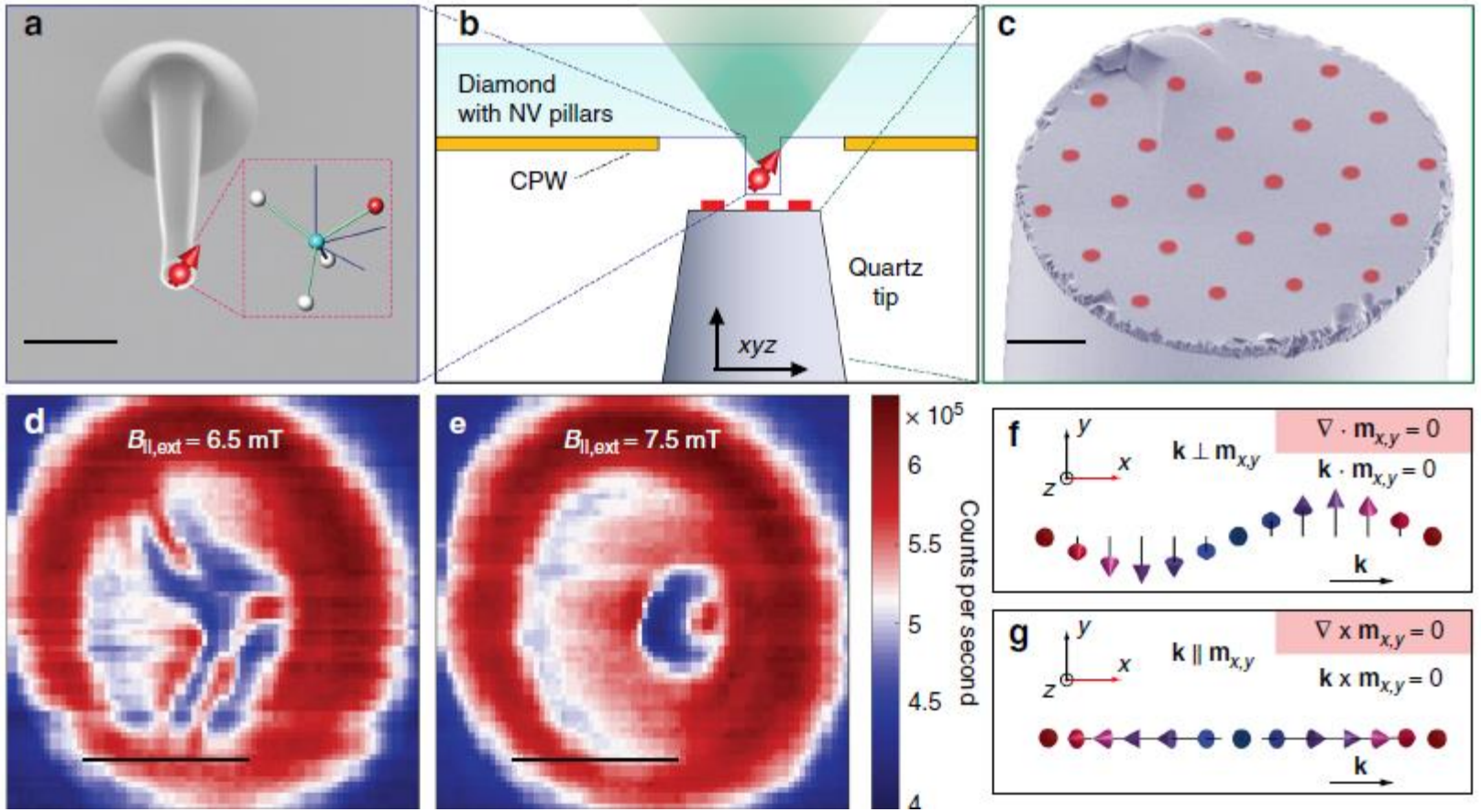






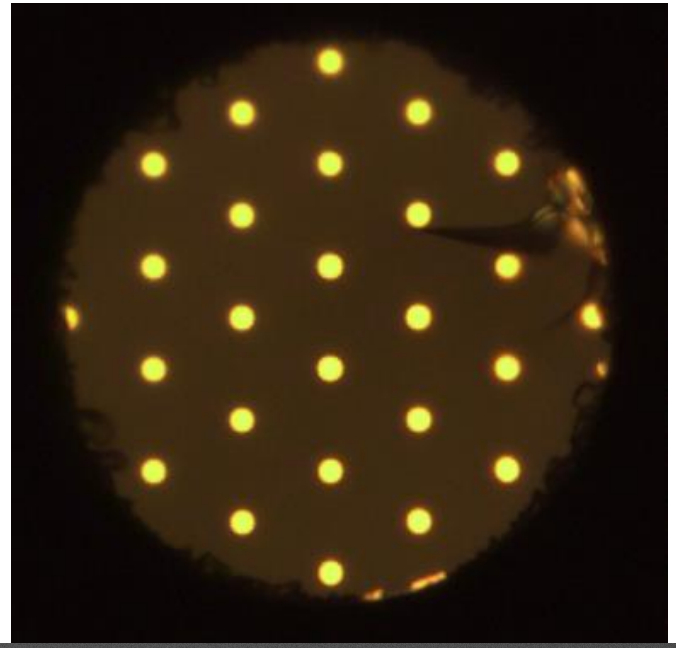
Diamond in gap not completely etched ?
Didn't change during one additional hour of etching (370 min total)
What aspect ration can be achieved with RIE ?

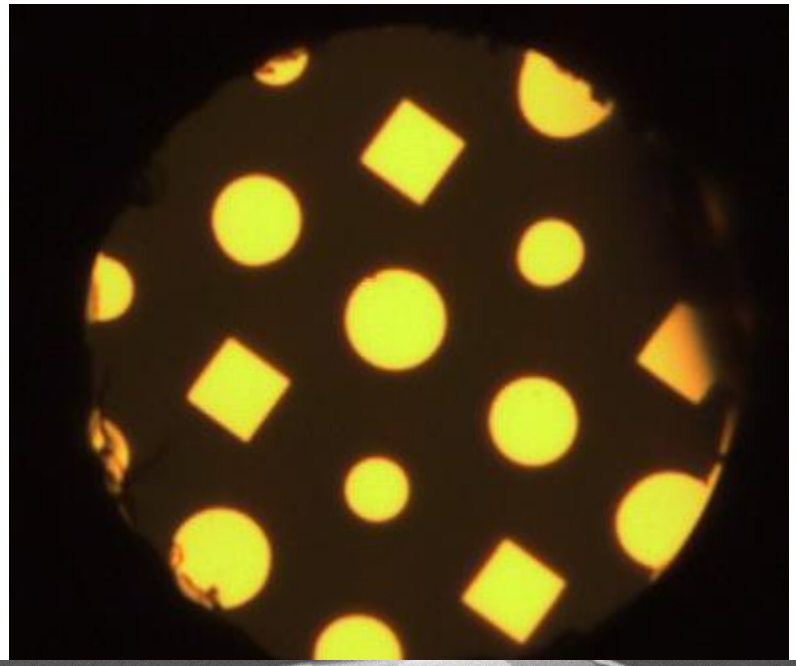
In parallel to getting diamond probe

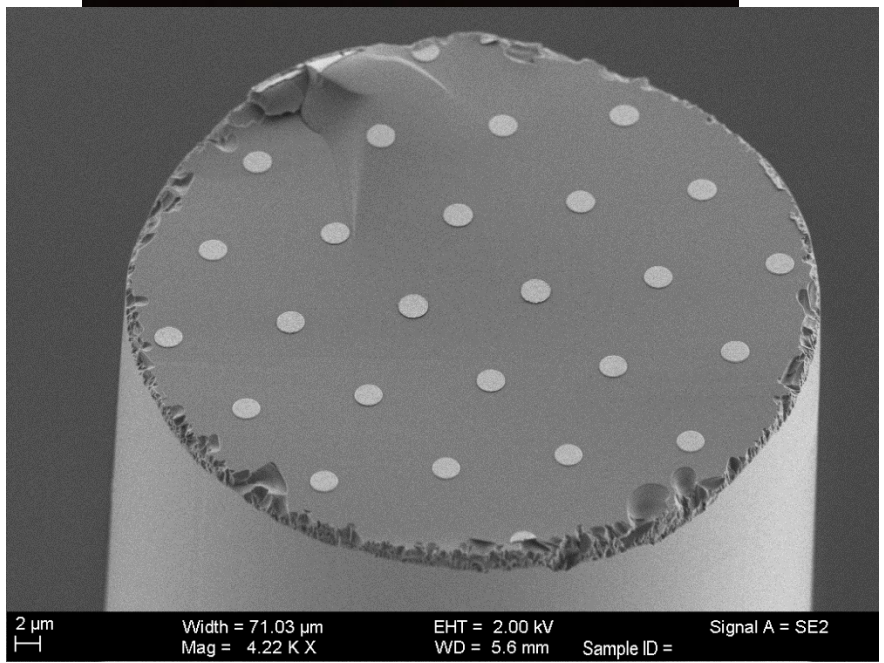


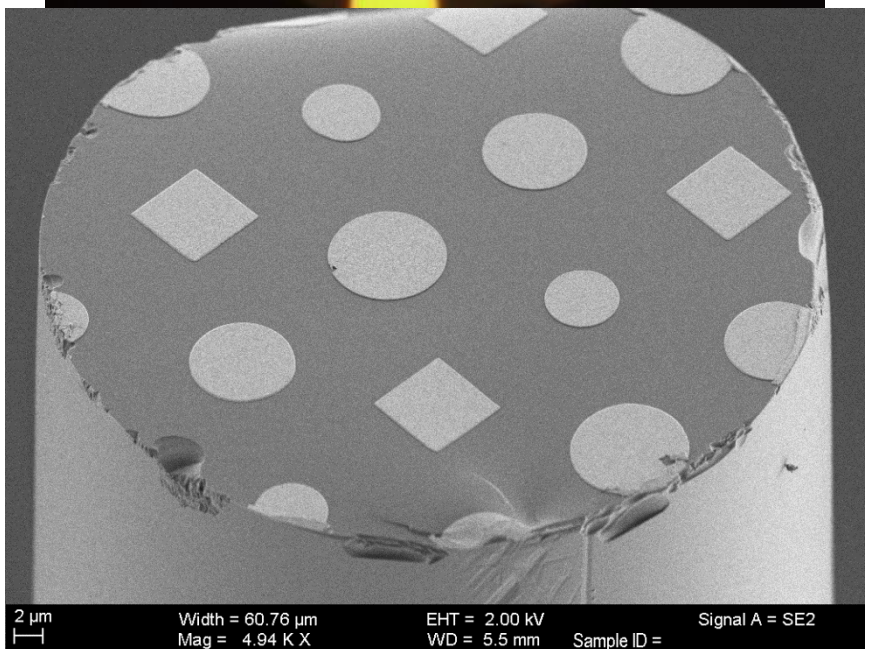
Y. Dovzhenko*, F. Casola*, S. Schlotter, **Tony X. Zhou** *et al, Nature Communications*. **9**, 2712 (2018). (*equal contribution)

Nanofab on tips









My favorite materials for Quantum Applications

Superconductors

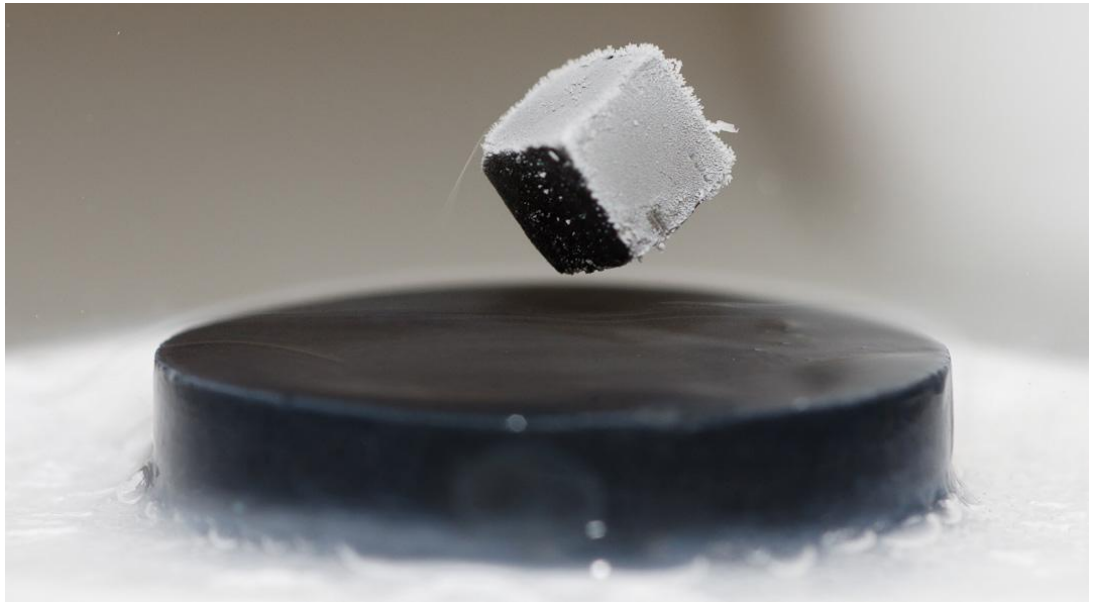
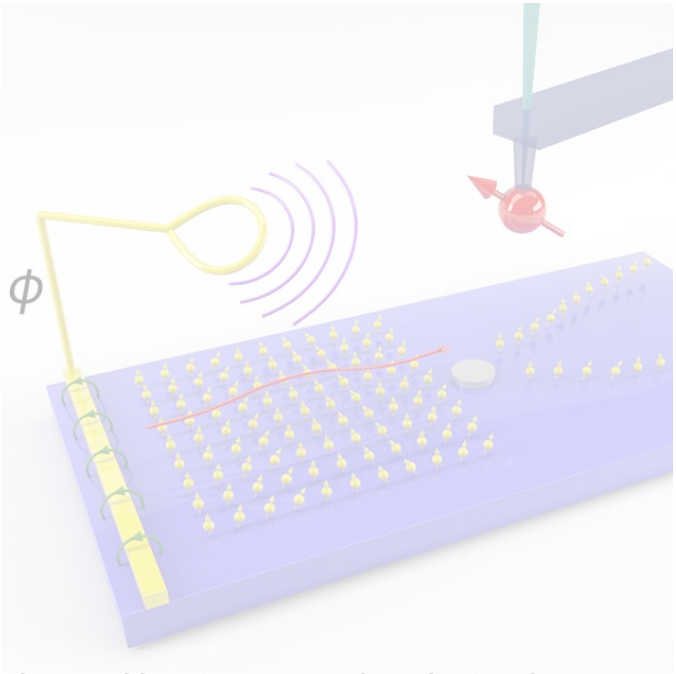


Photo:
https://www.extremetech.com/

Quantum Sensing by etching diamonds



https://qscience.org/co-design/

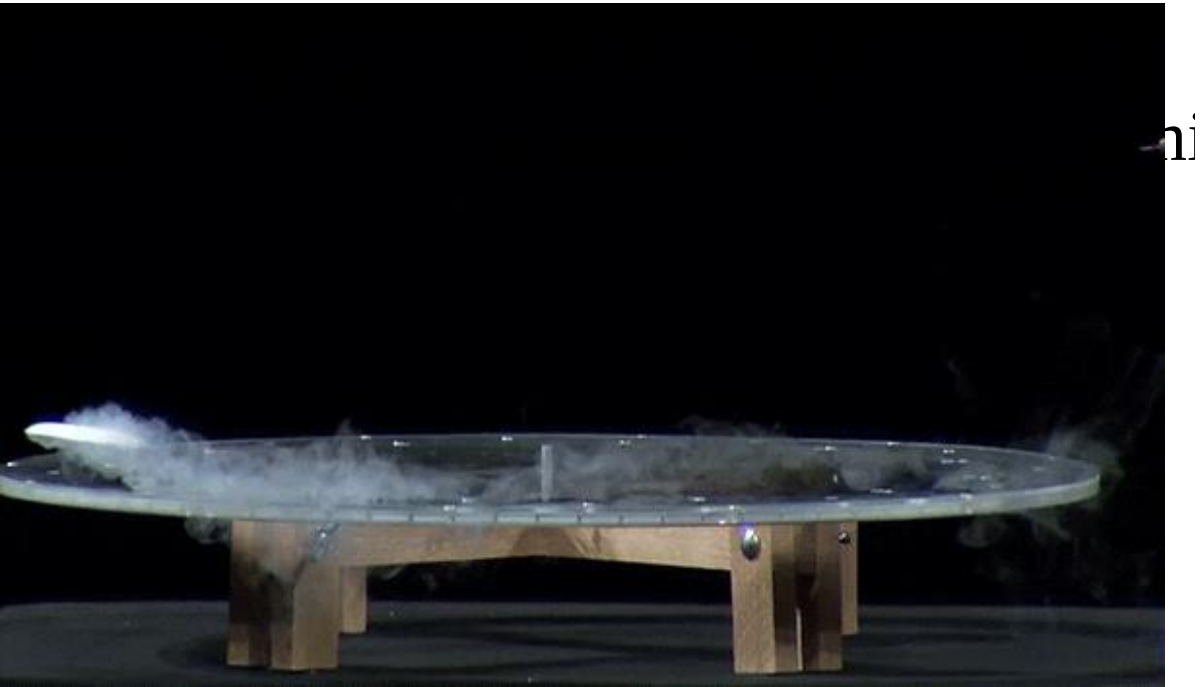
Photo:
https://www.pinterest.com/pin/675610381577582322/

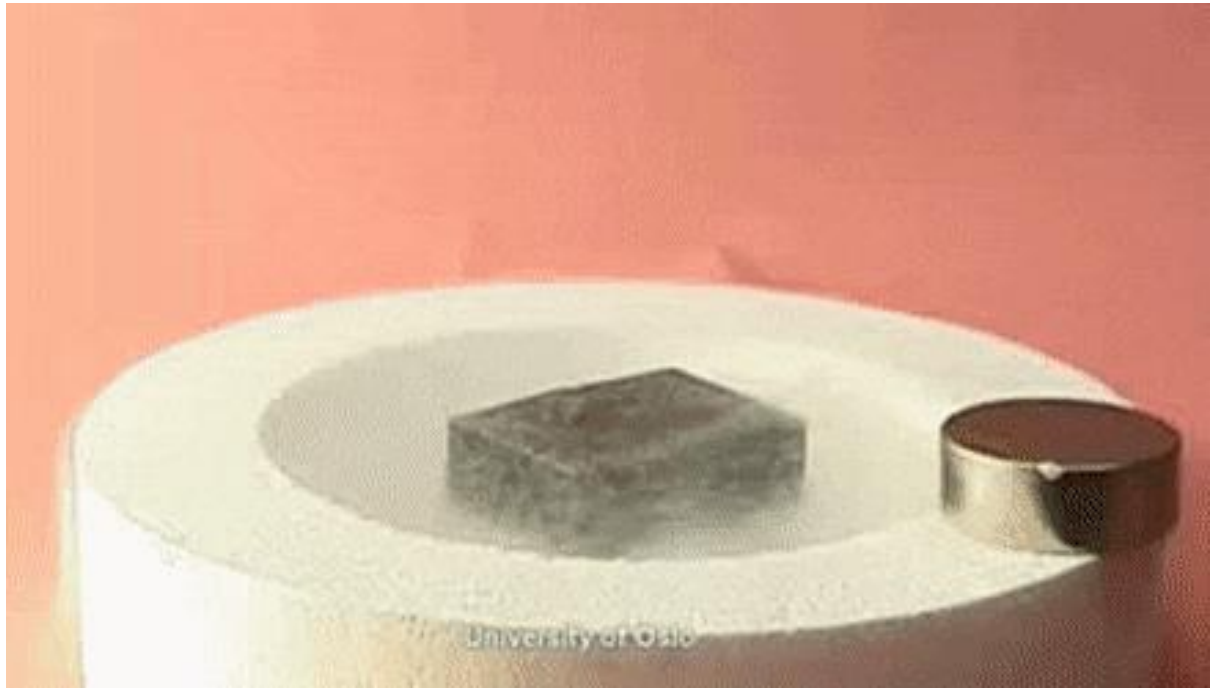
Applications

Low-Tc

1. High intensity electromagnets for MRI and NMR
2. High sensitivity particle detectors and magnetometers
3. Fast digital circuits (e.g. Josephson junctions)
4. Low loss RF and microwave filters

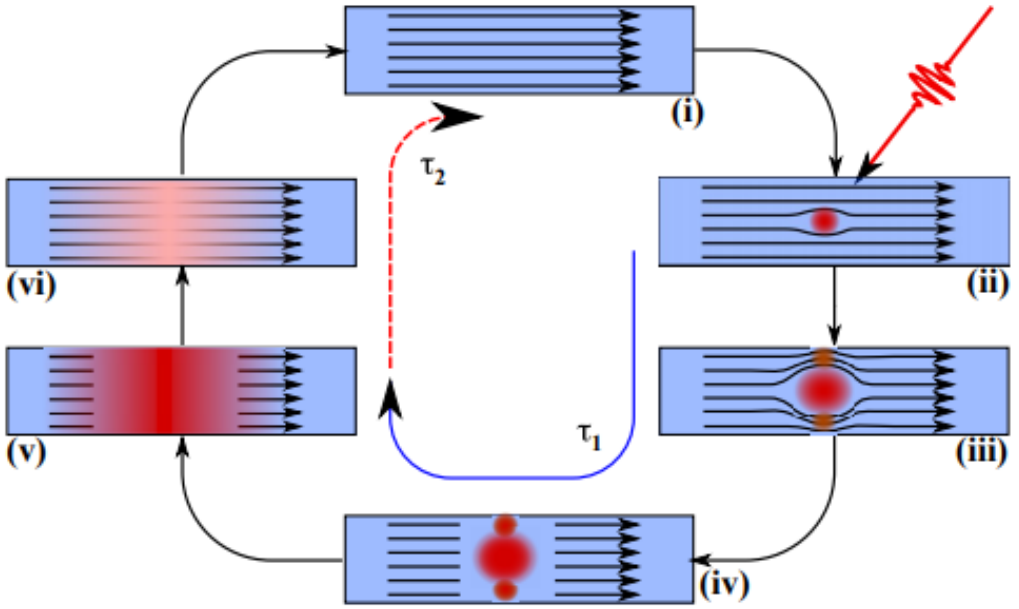
superconducting quantum interference device (SQUID)



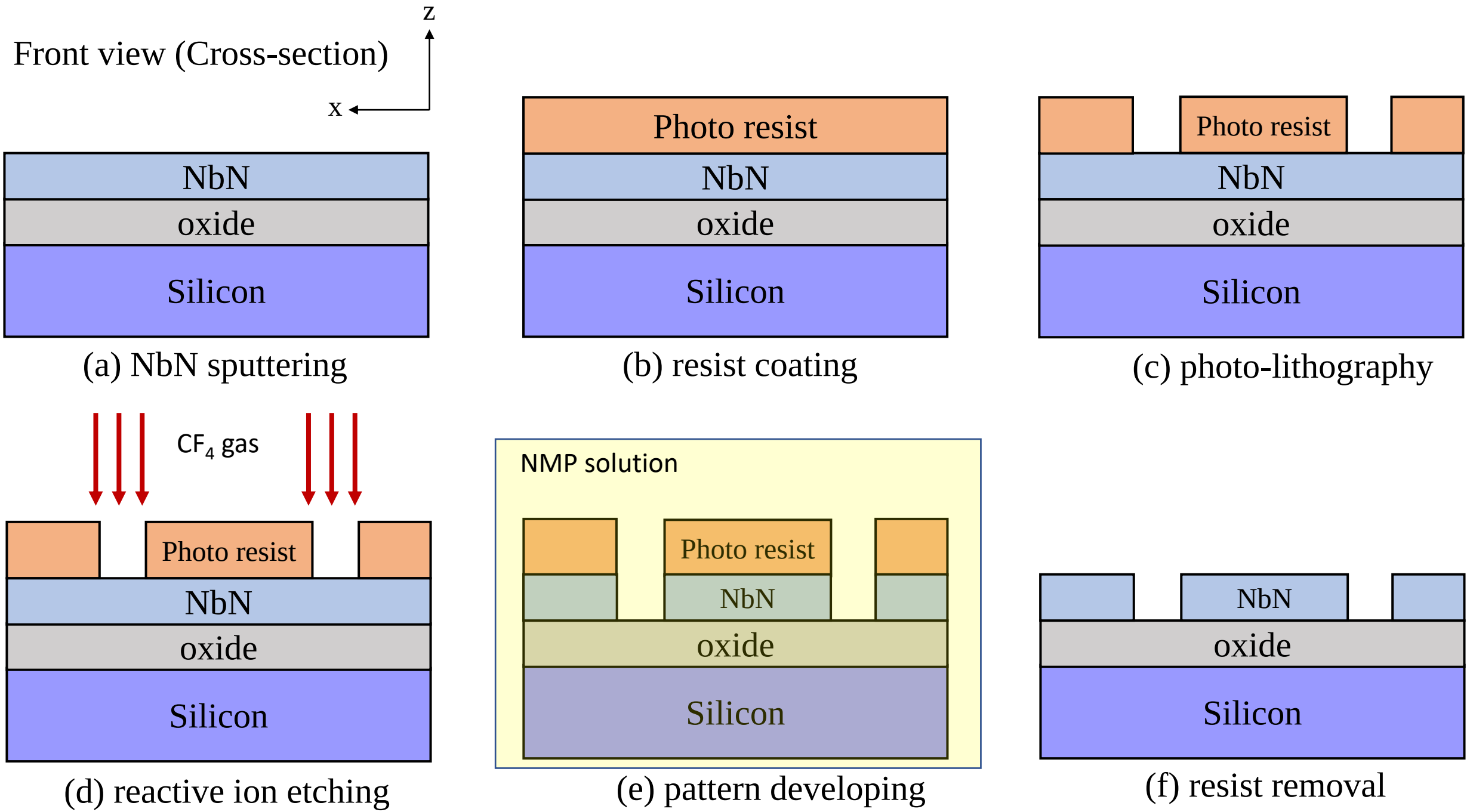


Superconducting nanowire single photon detector (SNSPD)

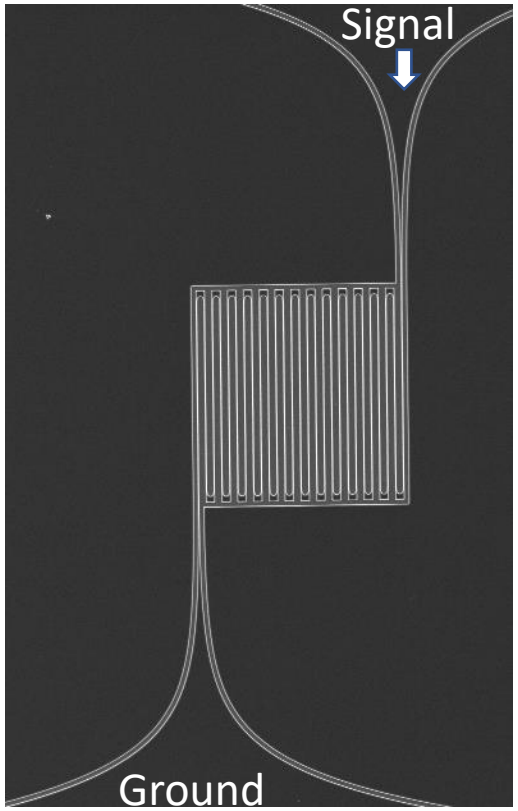
- Almost unity Detection Efficiency (DE)
- Single photon sensitivity up to $10\mu m$
- Jitter <100ps (e.g. Photonspot.com)
- Dark counts as low as 1 per day

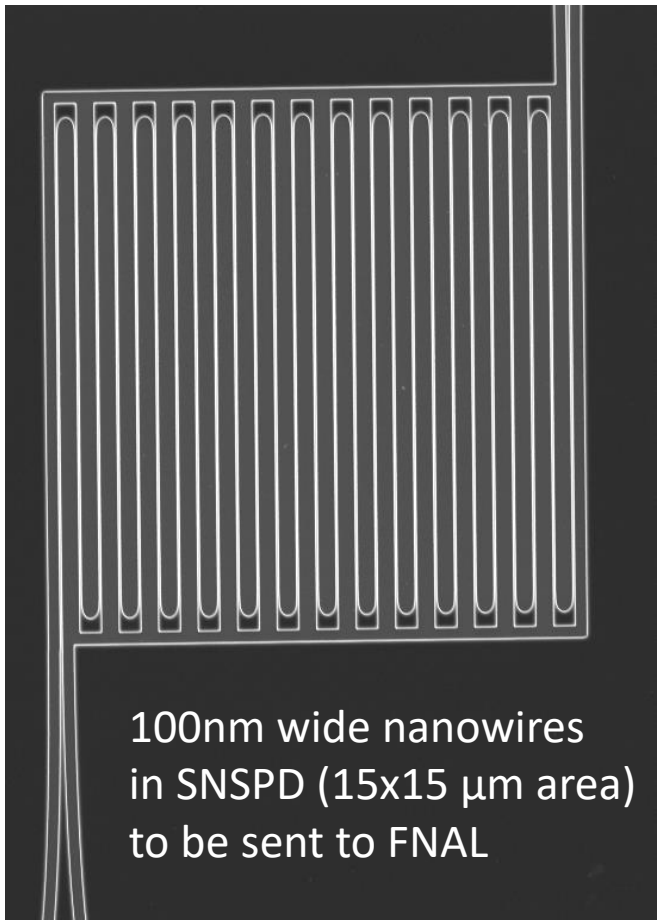


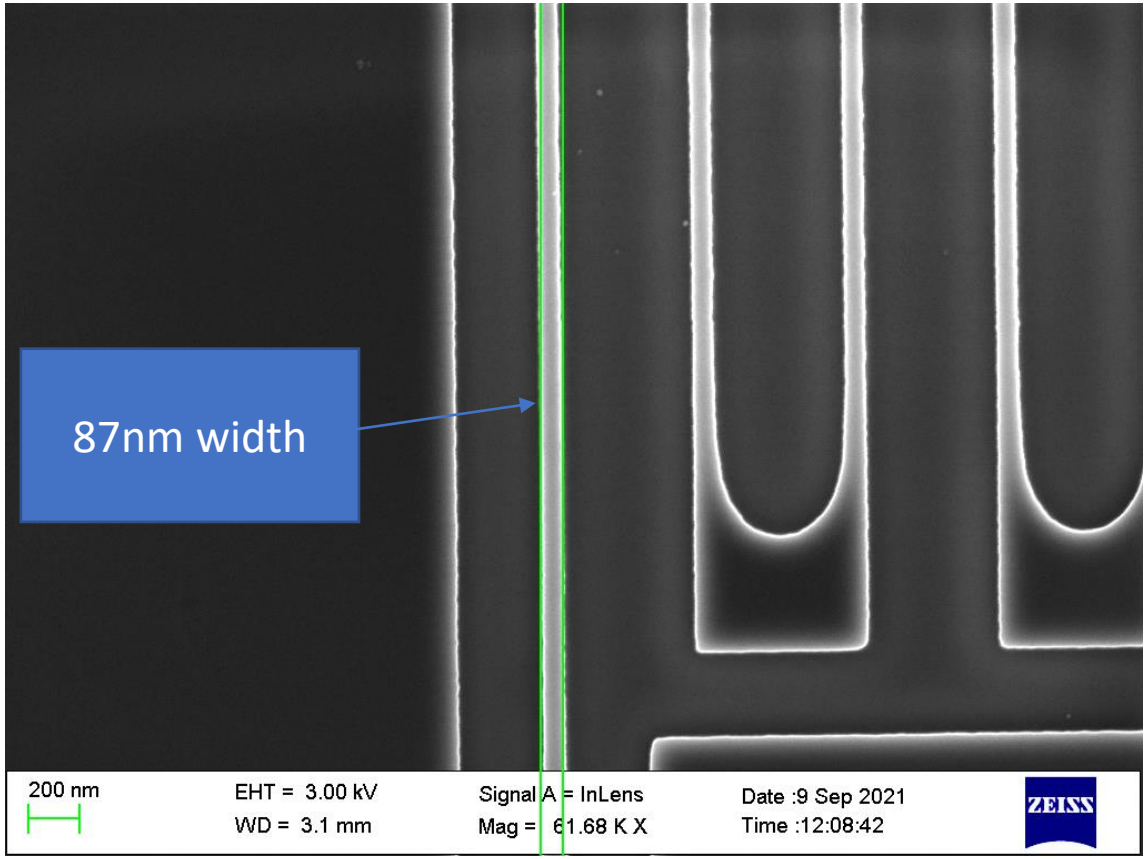
Natarajan, C.M. et al. 2012. Superconducting nanowire single-photon detectors: physics and applications. *Superconductor Science and Technology*. 25, 6 (Apr. 2012), 063001. DOI:https://doi.org/10.1088/0953-2048/25/6/063001.


Front view (Cross-section)
z
x
NbN
oxide
Silicon
(a) NbN sputtering
Photo resist
NbN
oxide
Silicon
(b) resist coating
Photo resist
NbN
oxide
Silicon
(c) photo-lithography
CF4 gas
Photo resist
NbN
oxide
Silicon
(d) reactive ion etching
NMP solution
Photo resist
NbN
oxide
Silicon
(e) pattern developing
NbN
oxide
Silicon
(f) resist removal

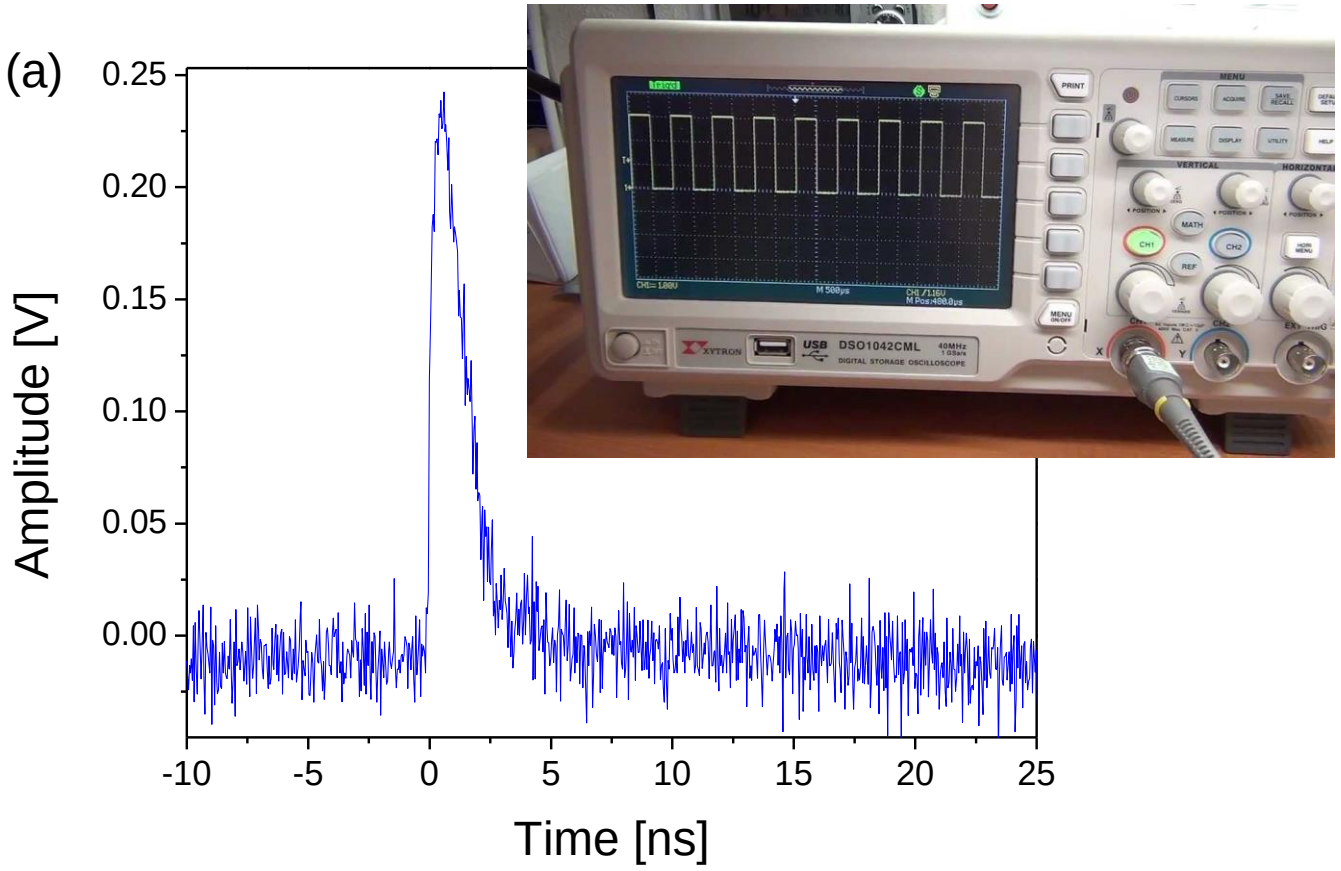
SNSPD

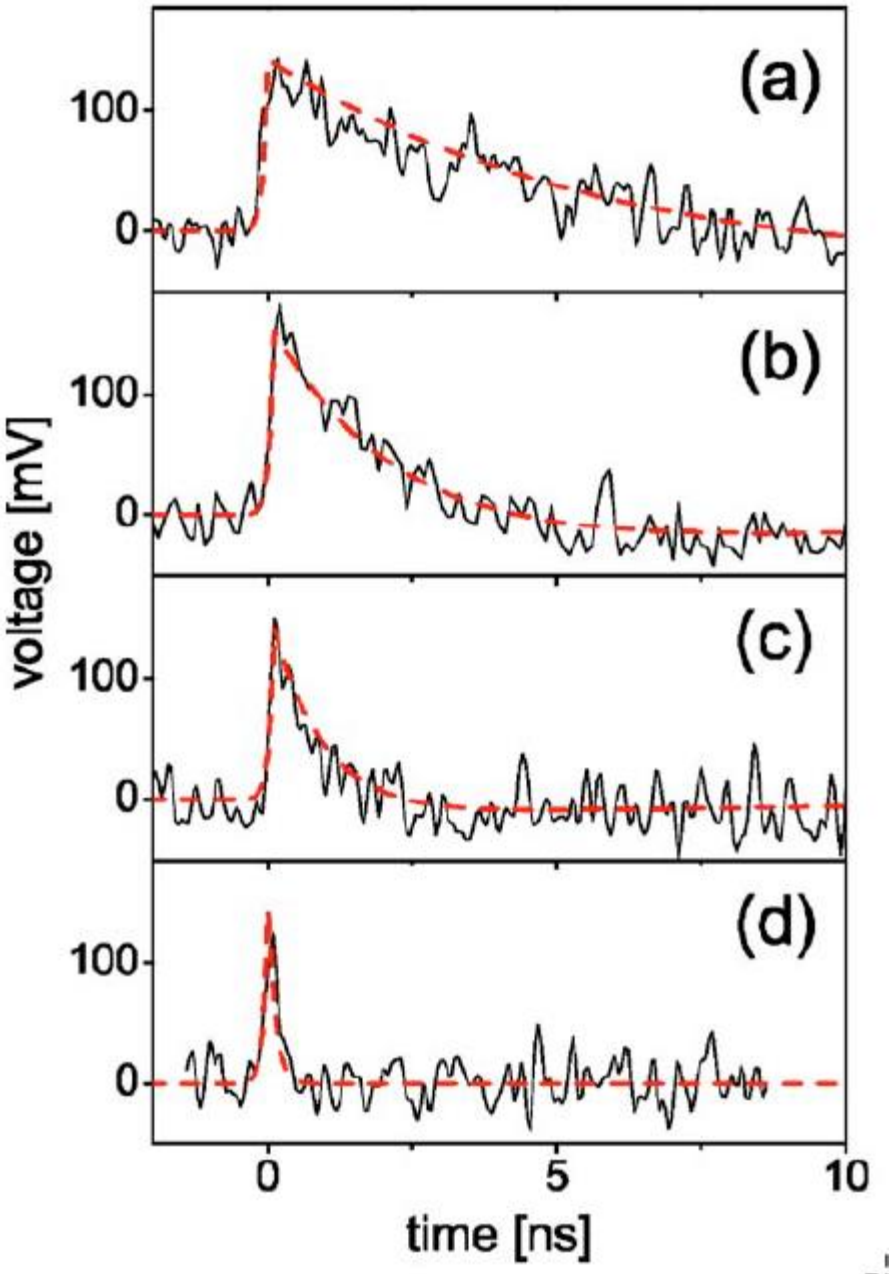

Signal
Ground


100nm wide nanowires
in SNSPD (15x15 µm area)
to be sent to FNAL


87nm width
200 nm
EHT = 3.00 kV
WD = 3.1 mm
Signal A = InLens
Mag = 61.68 K X
Date :9 Sep 2021
Time :12:08:42
ZEISS

NbN SNSPD

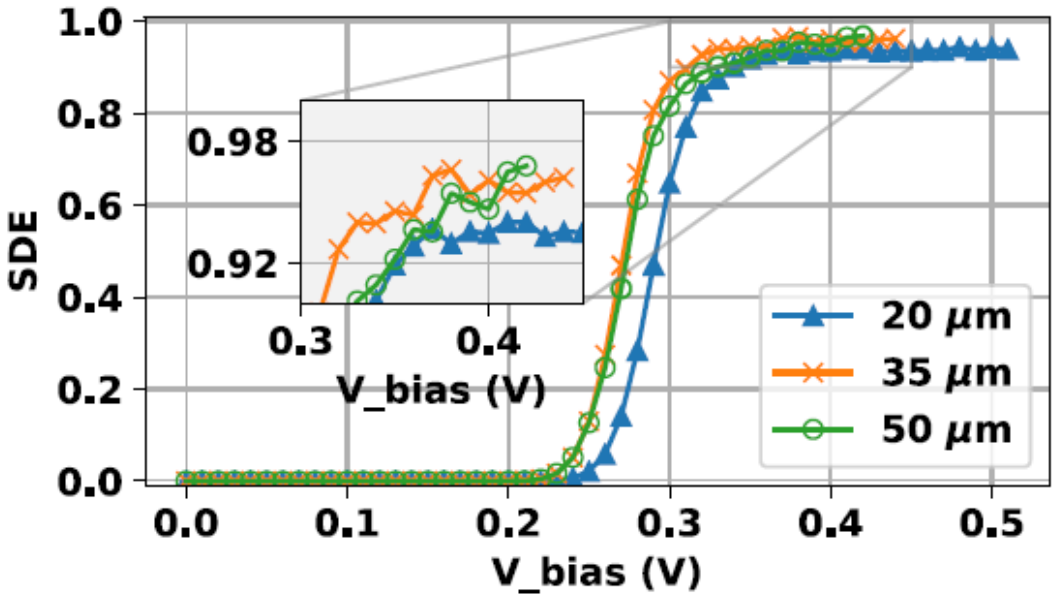




A. J. Kerman *et al.*, "Kinetic-inductance-limited reset time of superconducting nanowire photon counters," *Appl. Phys. Lett.*, vol. 88, no. 11, p. 111116, Mar. 2006, doi: 10.1063/1.2183810.

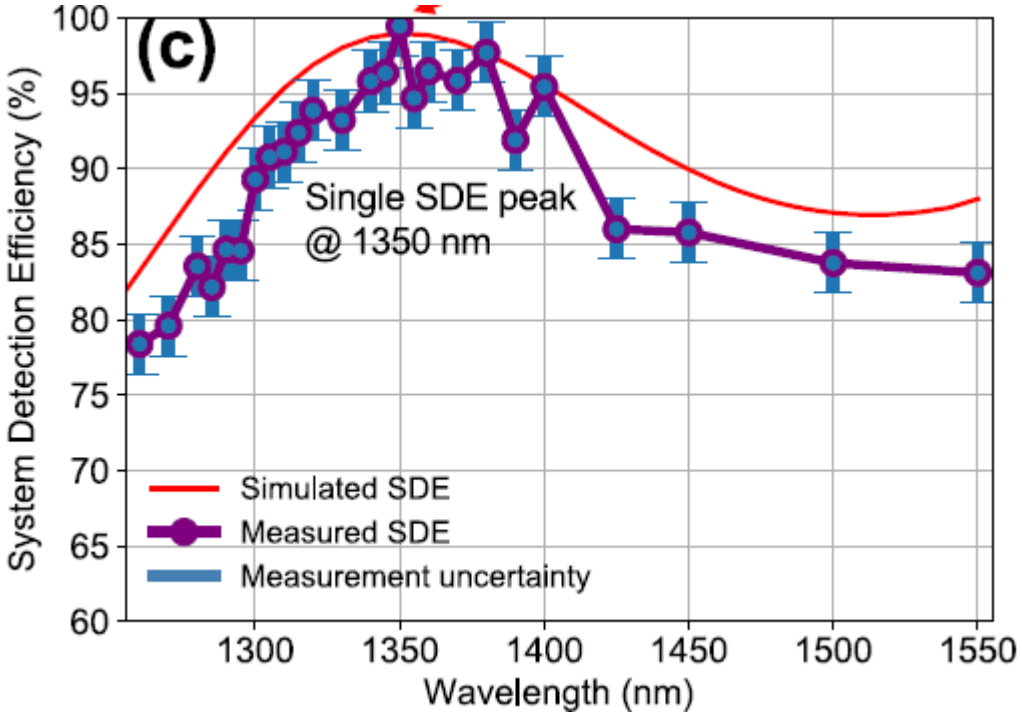
“Less crystalline, less perfect, the better!”
- Russ, Day1

Amorphous MoSi, SDE 98% @1550nm



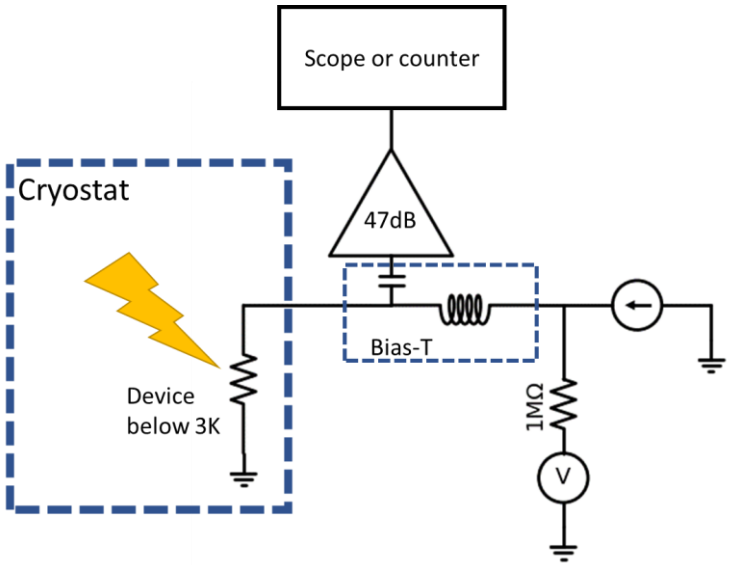
D. V. Reddy *et al.*, *Optica, OPTICA*. **7**, 1649–1653 (2020).

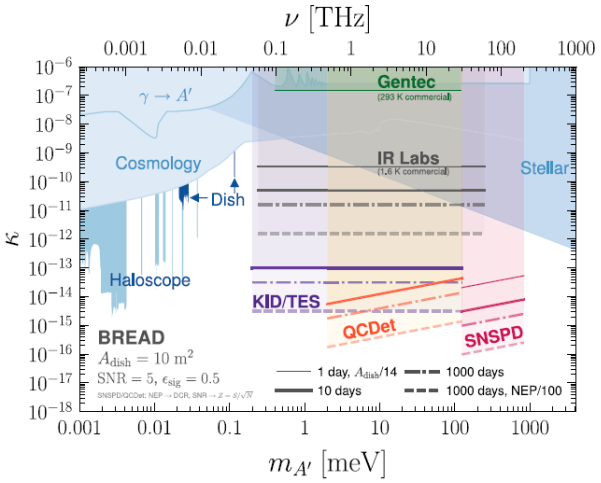
Polycrystalline NbTiN, SDE 98% @NIR



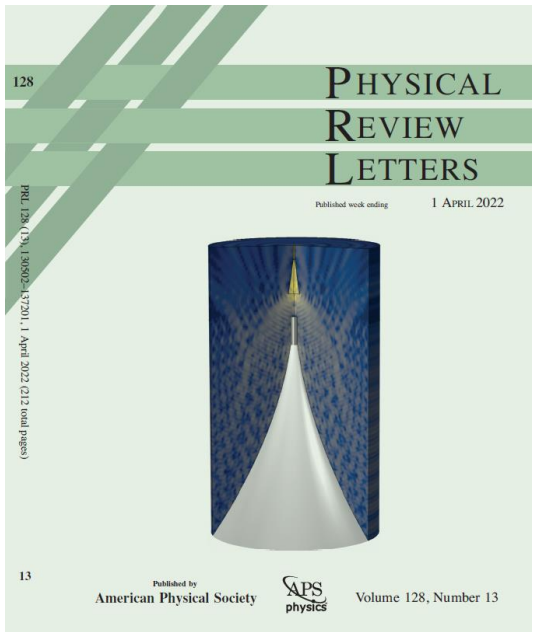
J. Chang *et al.*, *APL Photonics*. **6**, 036114 (2021).

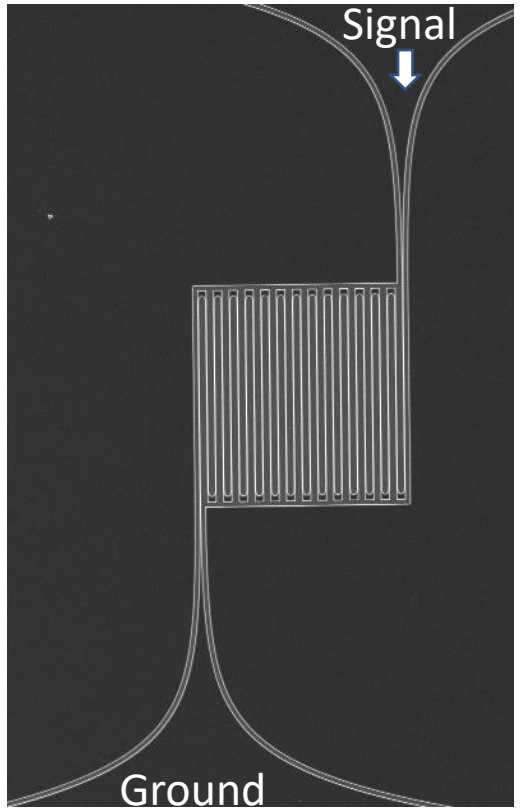
SNSPD experiment to be built in Fermi Lab

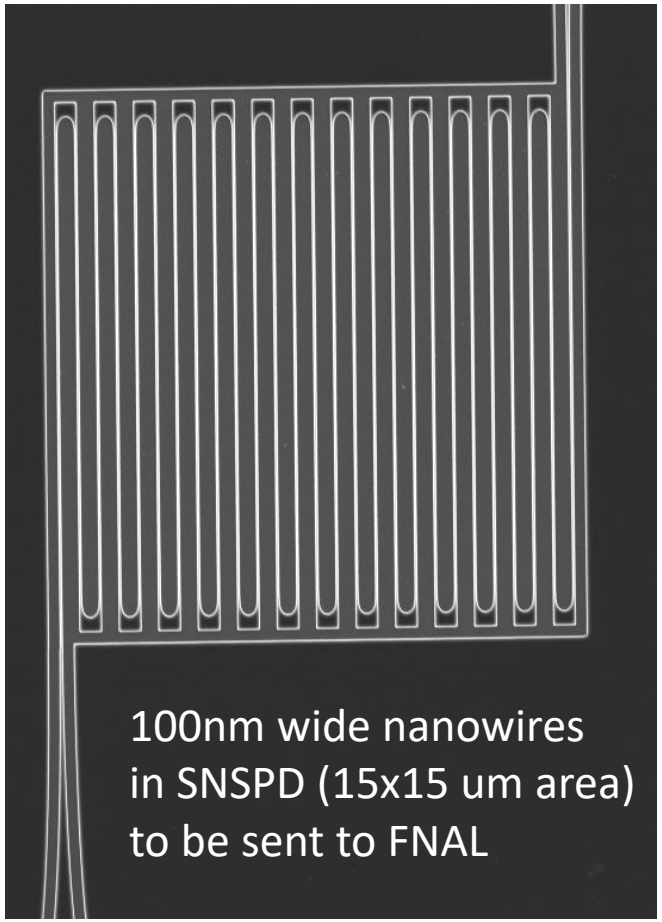




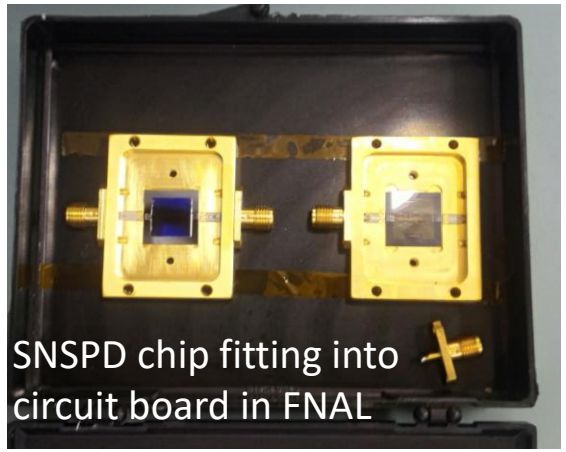
BREAD Collaboration *et al.*, *Phys. Rev. Lett.* **128**, 131801 (2022).





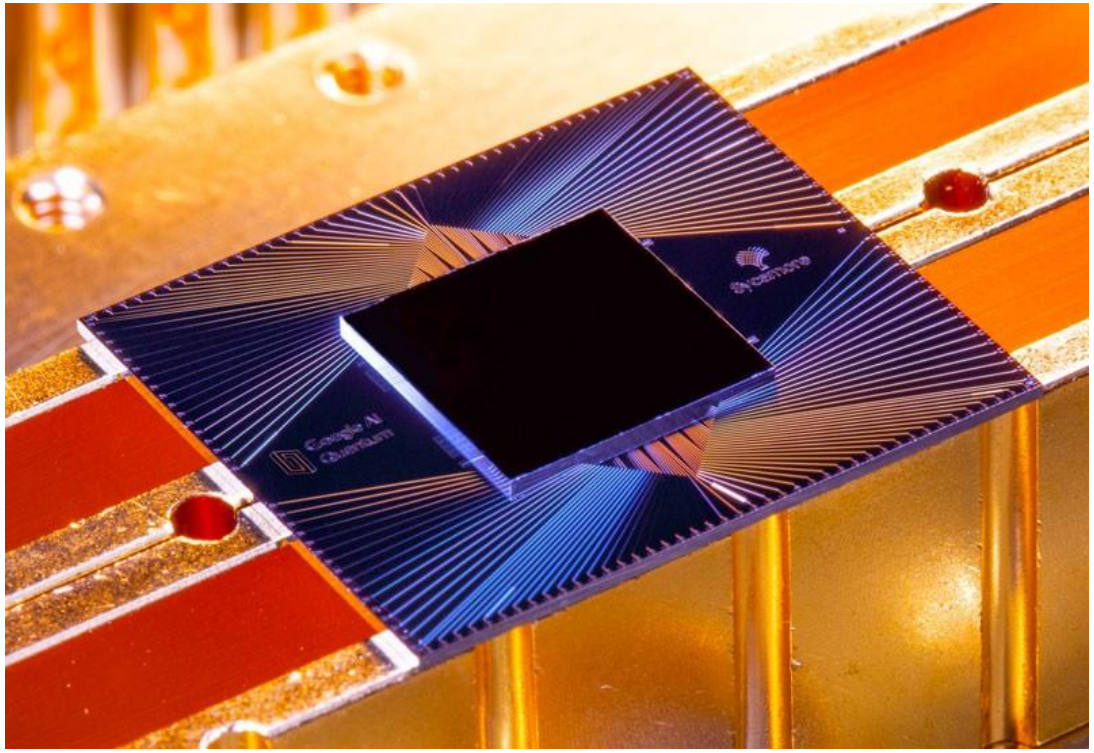


Experimental efforts from MIT



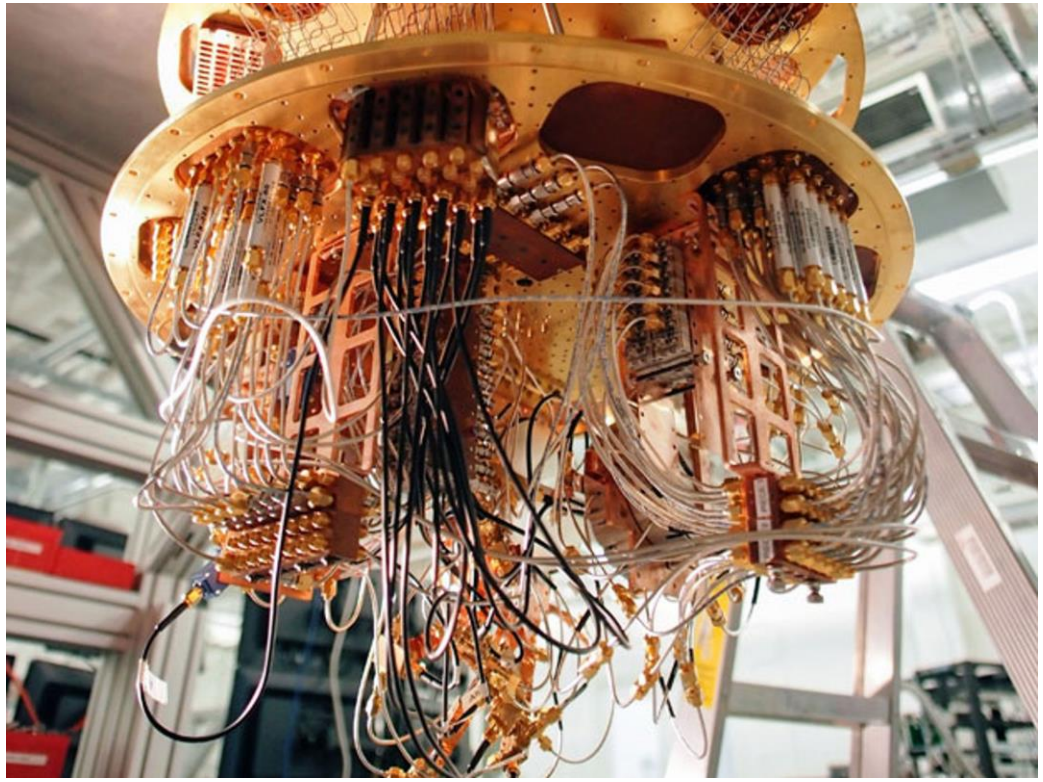
Why superconducting electronics

Google chip



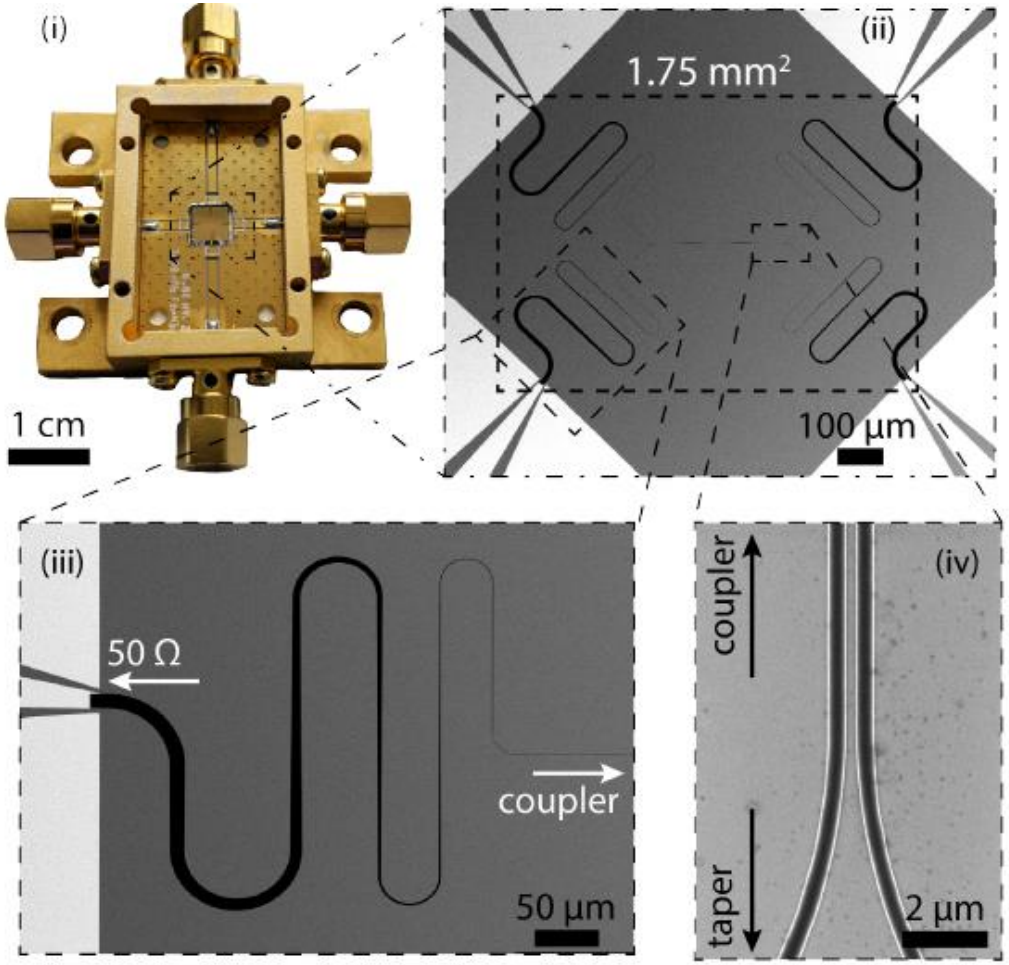
F. Arute *et al.*, *Nature*. **574**, 505–510 (2019).

What a mess!



https://spectrum.ieee.org/google-plans-to-demonstrate-the-supremacy-of-quantum-computing

RF circuits at QNN

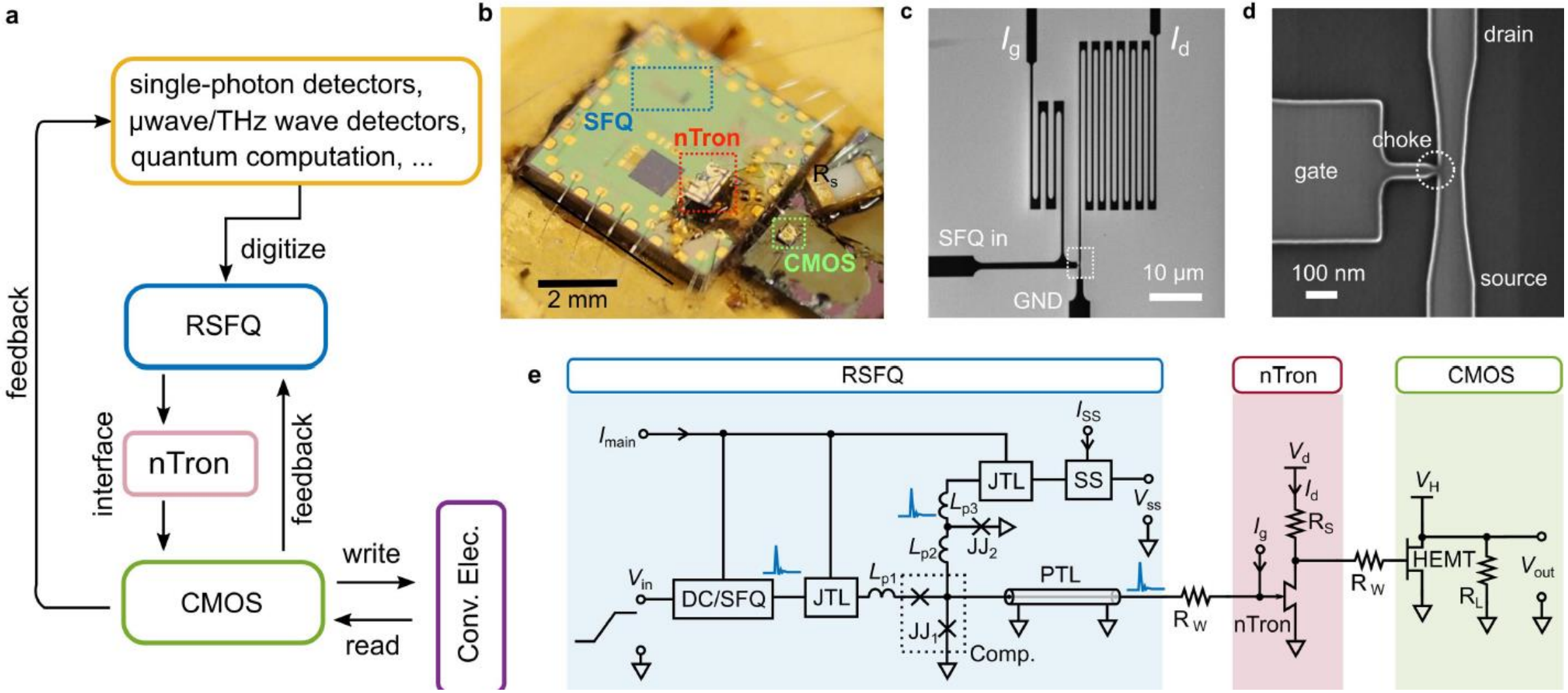


On-chip directional coupler based on high-impedance superconducting nanowires

- Balanced forward coupling
- Footprint reduction (almost two order of magnitude compared to standard directional coupler modules)

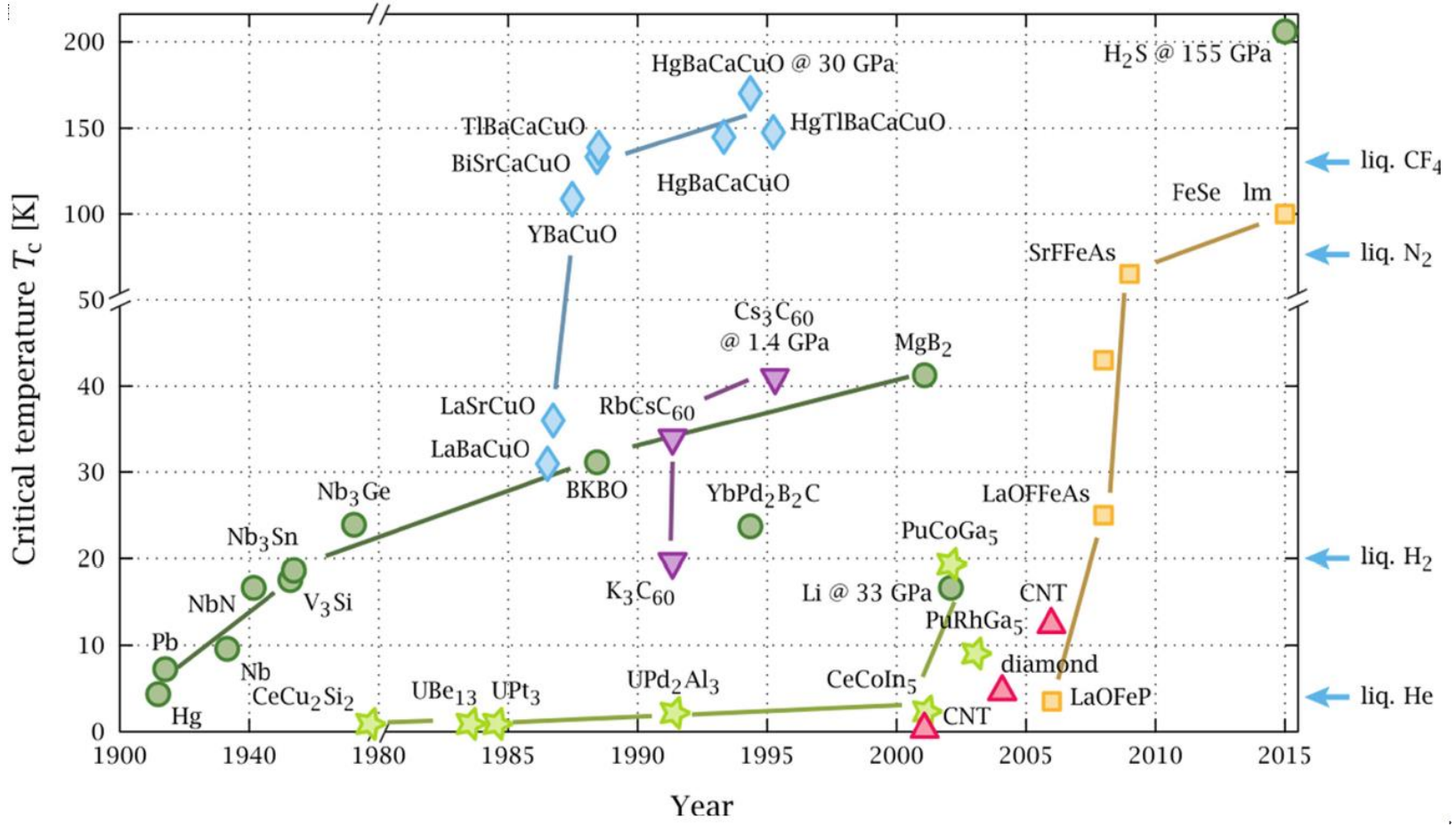
Colangelo, Marco et al. 2021. "Compact and Tunable Forward Coupler Based on High-Impedance Superconducting Nanowires." *Physical Review Applied* 15(2): 024064.

Interface between Cryo-circuits and Semiconductors



Zhao, Qing-Yuan et al. 2017. "A Nanocryotron Comparator Can Connect Single-Flux-Quantum Circuits to Conventional Electronics." *Superconductor Science and Technology* 30(4): 044002.

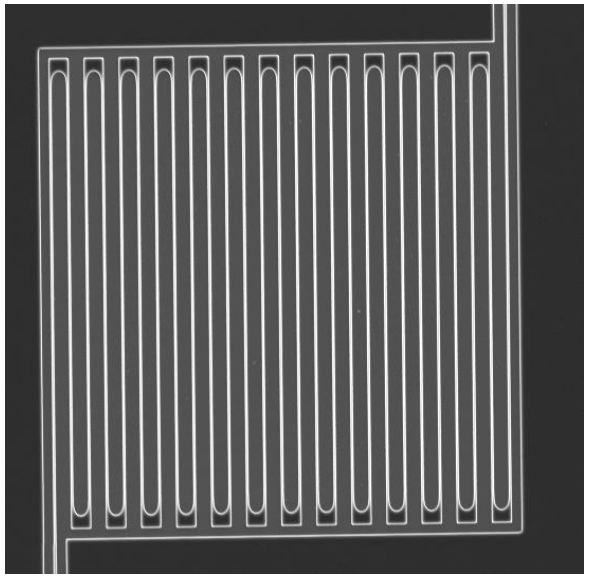
High Tc superconductors

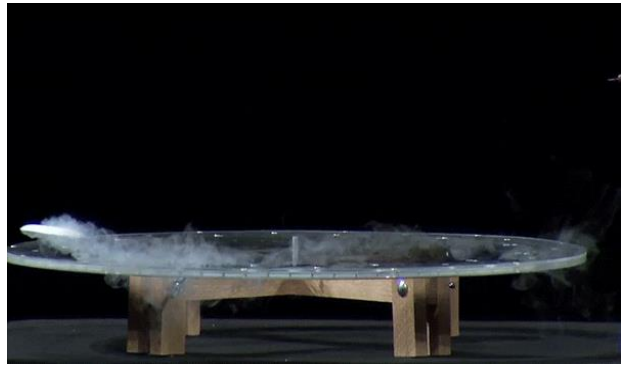


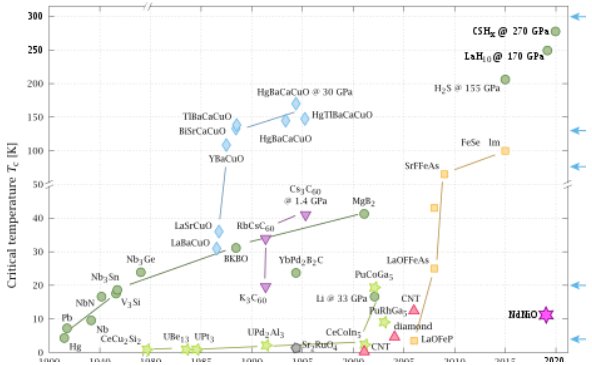
R. A. Dunlap, *High temperature superconductivity* (IOP Publishing, 2019; https://iopscience.iop.org/book/978-1-64327-690-8).

My favorite materials for Quantum Applications

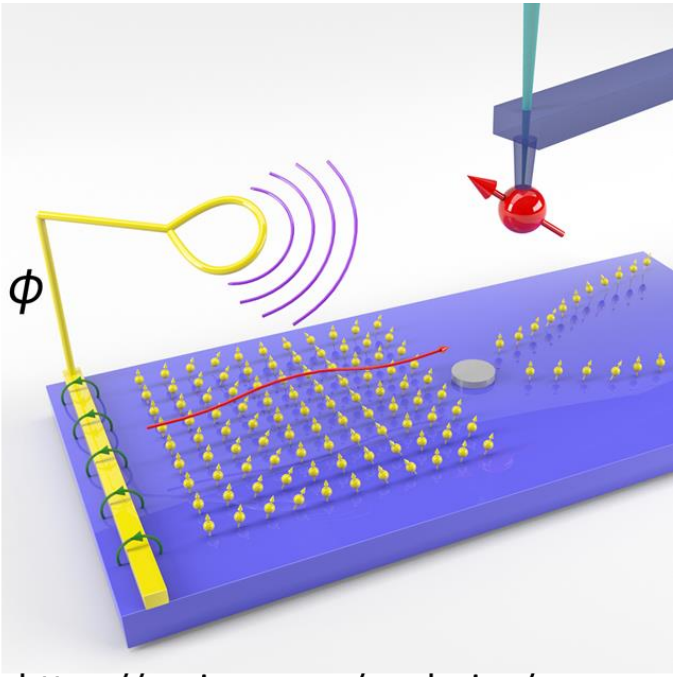
Quantum internet, computing, memory by etching superconductor







Quantum Sensing by etching diamonds



https://qscience.org/co-design/

Yacoby Group

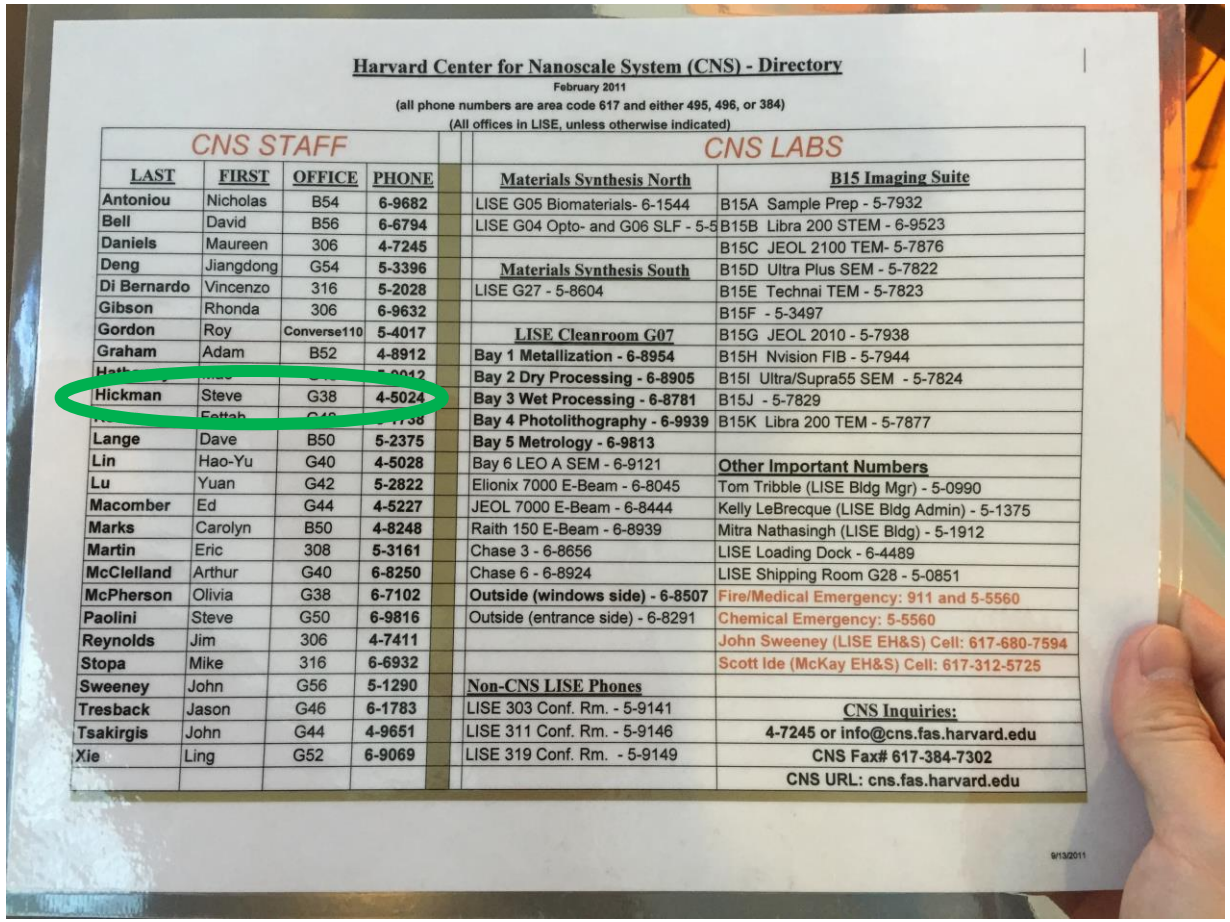
Funding:
- Gordon and Betty Moore Foundation's
- Army Research Office
- National Science Foundation NNCI

Collaborations:

- CNS staff members (especially to Ling)
- Ron Walsworth's group (diamond annealing and especially collaboration)
- Loncar group (Discussion and acid clean facility)
- Kim group (collaboration and friendship with early members)
- Nian Sun group at Northeastern

Wet Bench Quiz

1. Describe the process of performing an emergency shut-down of a wet bench:
   - Stop doing all experiments
   - Press the red button (emergency manual override)
   - Lower the glass front
   - If there is a fire and carbon dioxide is not activated, then pull down the fire alarm.
2. State the location of the first aid kit:
   - It is located in the gowning area



Harvard Center for Nanoscale System (CNS) - Directory

February 2011

(all phone numbers are area code 617 and either 495, 496, or 384)

(All offices in LISE, unless otherwise indicated)

CNS STAFF

LAST	FIRST	OFFICE	PHONE
Antoniou	Nicholas	B54	6-9682
Bell	David	B56	6-6794
Daniels	Maureen	306	4-7245
Deng	Jiangdong	G54	5-3396
Di Bernardo	Vincenzo	316	5-2028
Gibson	Rhonda	306	6-9632
Gordon	Roy	Converse110	5-4017
Graham	Adam	B52	4-8912
[illegible]			
Hickman	Steve	G38	4-5024
[illegible]			
Lange	Dave	B50	5-2375
Lin	Hao-Yu	G40	4-5028
Lu	Yuan	G42	5-2822
Macomber	Ed	G44	4-5227
Marks	Carolyn	B50	4-8248
Martin	Eric	308	5-3161
McClelland	Arthur	G40	6-8250
McPherson	Olivia	G38	6-7102
Paolini	Steve	G50	6-9816
Reynolds	Jim	306	4-7411
Stopa	Mike	316	6-6932
Sweeney	John	G56	5-1290
Tresback	Jason	G46	6-1783
Tsakirgis	John	G44	4-9651
Xie	Ling	G52	6-9069

CNS LABS

Materials Synthesis North	B15 Imaging Suite
LISE G05 Biomaterials- 6-1544	B15A Sample Prep - 5-7932
LISE G04 Opto- and G06 SLF - 5-5	B15B Libra 200 STEM - 6-9523
	B15C JEOL 2100 TEM- 5-7876
Materials Synthesis South	B15D Ultra Plus SEM - 5-7822
LISE G27 - 5-8604	B15E Technai TEM - 5-7823
	B15F - 5-3497
LISE Cleanroom G07	B15G JEOL 2010 - 5-7938
Bay 1 Metallization - 6-8954	B15H Nvision FIB - 5-7944
Bay 2 Dry Processing - 6-8905	B15I Ultra/Supra55 SEM - 5-7824
Bay 3 Wet Processing - 6-8781	B15J - 5-7829
Bay 4 Photolithography - 6-9939	B15K Libra 200 TEM - 5-7877
Bay 5 Metrology - 6-9813	
Bay 6 LEO A SEM - 6-9121	**Other Important Numbers**
Elionix 7000 E-Beam - 6-8045	Tom Tribble (LISE Bldg Mgr) - 5-0990
JEOL 7000 E-Beam - 6-8444	Kelly LeBrecque (LISE Bldg Admin) - 5-1375
Raith 150 E-Beam - 6-8939	Mitra Nathasingh (LISE Bldg) - 5-1912
Chase 3 - 6-8656	LISE Loading Dock - 6-4489
Chase 6 - 6-8924	LISE Shipping Room G28 - 5-0851
Outside (windows side) - 6-8507	Fire/Medical Emergency: 911 and 5-5560
Outside (entrance side) - 6-8291	Chemical Emergency: 5-5560
	John Sweeney (LISE EH&S) Cell: 617-680-7594
	Scott Ide (McKay EH&S) Cell: 617-312-5725
Non-CNS LISE Phones	
LISE 303 Conf. Rm. - 5-9141	**CNS Inquiries:**
LISE 311 Conf. Rm. - 5-9146	4-7245 or info@cns.fas.harvard.edu
LISE 319 Conf. Rm. - 5-9149	CNS Fax# 617-384-7302
	CNS URL: cns.fas.harvard.edu

9/13/2011

Superconductivity Team at MIT

Prof. Karl K. Berggren

Emma Batson (Grad Student)

Matteo Castellani (Grad Student)

Marco Colangelo (Grad Student)

Stewart Koppell (Post-Doc)

Owen Medeiros (Grad Student)

Dip Joti Paul (Grad Student)

Tony Zhao (Post-Doc)

<u>Graduated/Former</u>

Nathan Abebe
Lucy Archer
Reza Baghdadi
Francesco Bellei
Brenden Butters
Niccolo Calandri
Ilya Charaev
Ignacio Estay Forno
Andrew Dane
Yachin Ivry
Glenn Martinez
Adam McCaughan
Faraz Najafi
Murat Onen
Ashley Qu
Kristen Sunter
Emily Toomey
Hao-Zhu Wang
Qing-Yuan Zhao
Di Zhu

Thank you to Lara Ranieri and Rinske Wijtmans for assistance in preparing these slides for presentation

Questions?

Other superconducting collaborators:

- National Institute of Standards and Technology (NIST)
- MIT Lincoln Laboratory (LL)
- Caltech Jet Propulsion Laboratory (JPL)
- Fermi Lab (FNAL)
- Brookhaven National Lab (BNL)
- Argon National Lab (ANL)