Research Spotlight Forum

6.4.19 Quantum Information Sciences

Purdue Quantum Science and Engineering Institute (PQSEI); Quantum Matter/Materials and Devices for Quantum Information Sciences

PRESENTED BY:

Yong P. Chen, Director of PQSEI; yongchen@purdue.edu

Sandia National Laboratories | Georgia Institute of Technology | ILLINOIS | PURDUE UNIVERSITY | THE UNIVERSITY OF TEXAS AT AUSTIN | THE UNIVERSITY OF NEW MEXICO | NM STATE UNIVERSITY | NEW MEXICO TECH SCIENCE • ENGINEERING • RESEARCH UNIVERSITY

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ABOUT Myself

- Brief biography: MS in mathematics from MIT (1999), PhD in electrical engineering from Princeton University (2005), and did a postdoc in atomic physics at Rice University. Joined Purdue faculty in 2007, currently **Professor of Physics & Astronomy and Electrical & Computer Engineering** as well as the Associate Director of Research for Birck Nanotechnology Center, and Inaugural **Director of Purdue Quantum Science and Engineering Institute** (PQSEI). Assoc. Editor for AIP-AVS Quantum Science and Foreign PI in WPI-AIMR (International Material Research Center) in Tohoku Univ., Japan. Received NSF Career Award, Young Investigator Awards from DOD and ACS, IBM Faculty Award, a Horiba Award in Japan, Villum Investigator Award in Denmark, and an elected APS Fellow (2016).

- Research areas: Experimental **condensed matter physics & nanoscience** (graphene/2D materials, topological insulators, 2D electrons/quantum Hall physics) and **atomic/molecular/optical (AMO)/quantum physics**/quantum photonics (cold atom Bose-Einstein condensation, cold molecules)

- Research group (Quantum Matter and Devices Lab: www.physics.purdue.edu/quantum) interests: "Making, Manipulating and Measuring Quantum Matter and Devices" (with potential applications such as energy, sensing and quantum technologies.), typically ~10 people @ Purdue (currently 5 PhD students (both PHYS and ECE), 2 postdocs, 4 undergrad/summer students)

- Purdue Quantum Science and Engineering Institute (PQSEI, https://engineering.purdue.edu/PQC): research areas in quantum materials/devices/photonics/chemistry/control-measurements/simulation/computing-information-algorithms-machine learning involving ~30 faculty from Depts of Physics (AMO, condensed matter..), Electrical Engineering (optics, nan), chemistry, materials, mechanical/biomedical/industrial/civil engineering, mathematics, computer science, even business school.

Keywords:

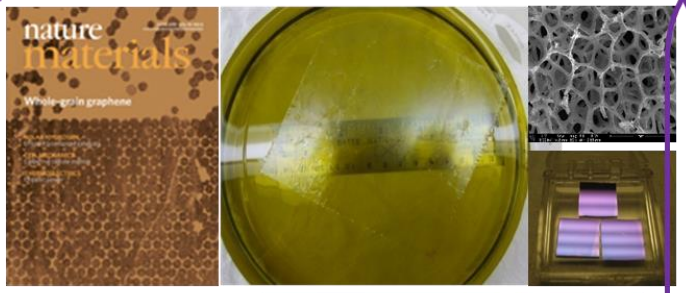
Graphene, 2D materials, topological insulators, spintronics, Josephson junctions, topological superconductors, quantum Hall, plasmonics, photodetectors, radiation detectors, thermal transport, thermoelectrics; Bose-Einstein condensates, cold molecules, photoassociaton; topological phases, synthetic gauge fields and spin-orbit coupling; quantum computing; quantum simulation; quantum materials; quantum devices; quantum photonics. see publication profile:

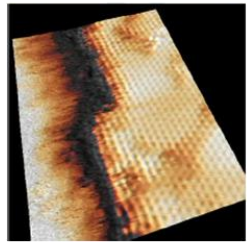
http://www.physics.purdue.edu/quantum/publications.php and https://scholar.google.com/citations?user=9EBAemEAAAAJ

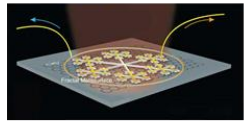
CURRENT WORK IN QUANTUM INFORMATION SCIENCES

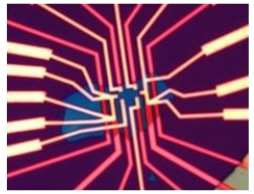
Quantum Matter and Devices (QMD) Laboratory – www.physics.purdue.edu/quantum

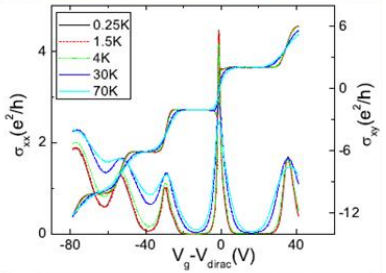
Graphene/2D materials

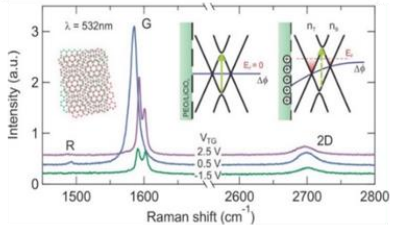


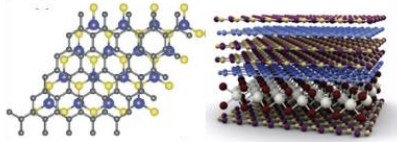






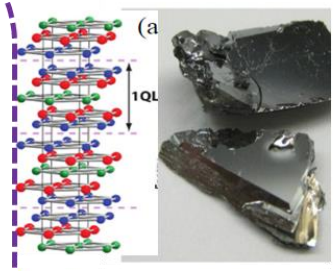


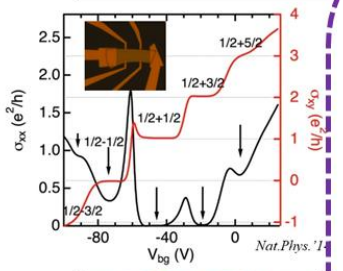


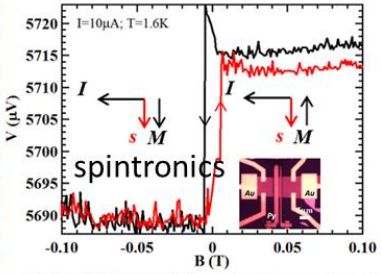


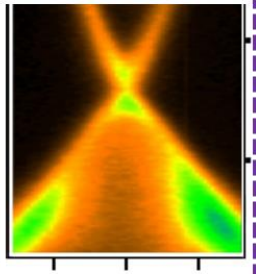
Insulator(h-BN);
Semiconductor
(TMDs – MoS_2, WS_2,..); [superconducts/magnets],
twisted bilayers/hybrids/vdW heterostructures…

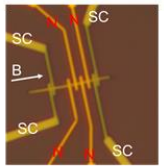
Topological insulators/materials

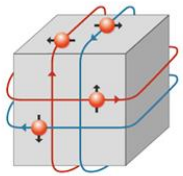


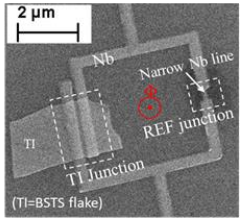


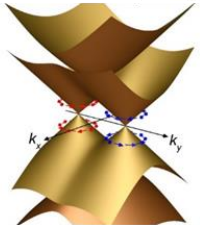


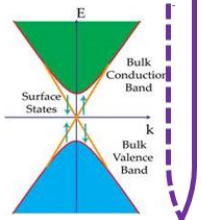








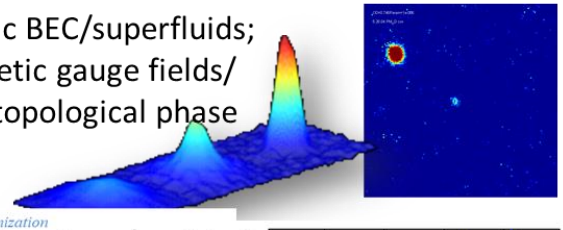


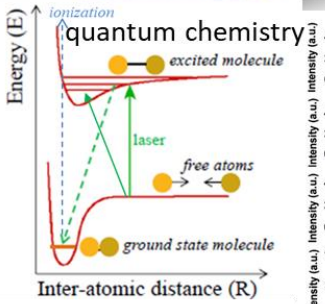


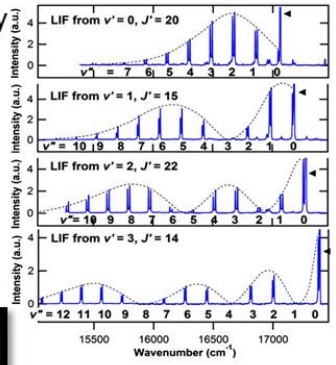
Topological superconductors/semimetals

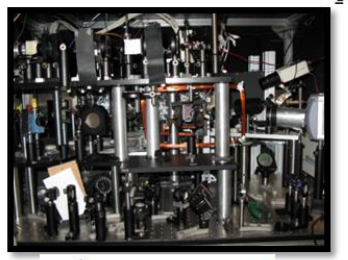
Quantum Optics/AMO physics

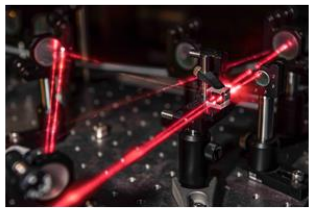
atomic BEC/superfluids;
synthetic gauge fields/
SOC/topological phase

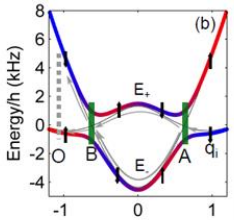


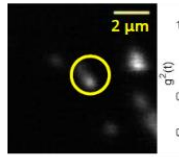


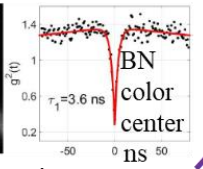












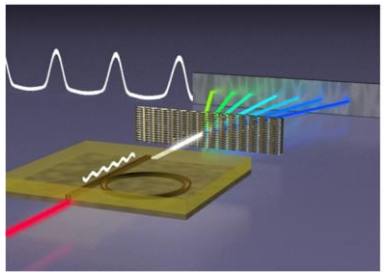
BN color center

quantum photonics/emitters

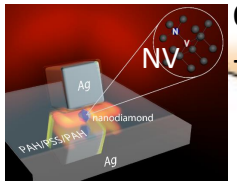
Purdue Quantum Science & Engineering Institute

A Center for Disruptive Quantum Technologies

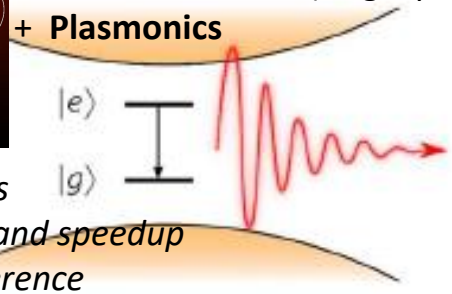
(Ultrafast) Quantum Photonics and Quantum Sensing



Quantum photonics:
Pulse-shaping of photons (time/frequency domain)
On-chip generation of Single/entangled photons;
Photonic "qudits" (high-dim) for quantum computing;
Quantum communications/imaging/"quantum radar"

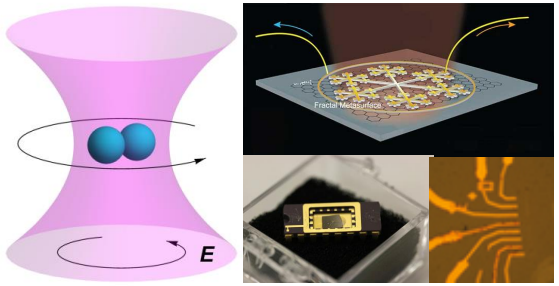


Quantum emitters (single photon sources)
+ **Plasmonics**



Use plasmonics enhancement and speedup to beat decoherence

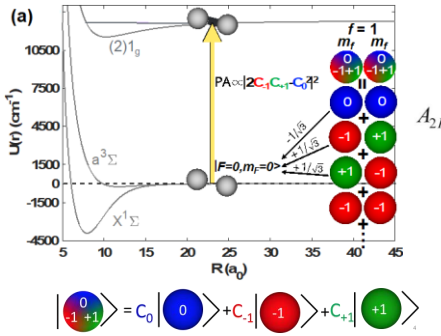
Ultrasensitive detectors for:



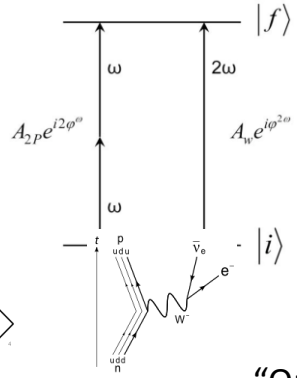
Force
Torque
Photon
Radiation
Magnetic Field
Nuclear Spins
(nanoscale NMR)

Quantum Control and Quantum Energy

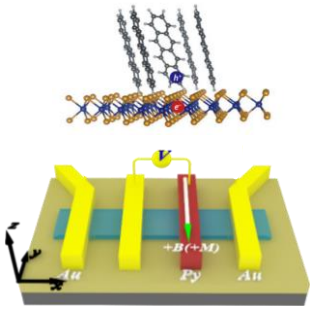
chemistry/catalysis



nuclear/radioactivity

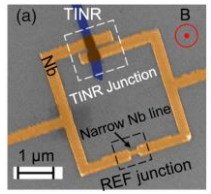


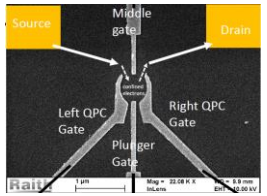
Photovoltaic/ photosynthesis



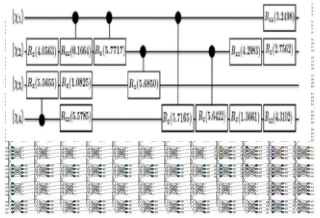
"Quantum/spin battery"

Quantum Computing and Quantum Informatics





Quantum materials/devices platforms: Josephson junctions; quantum dots; Topological materials/states & topological quantum computation



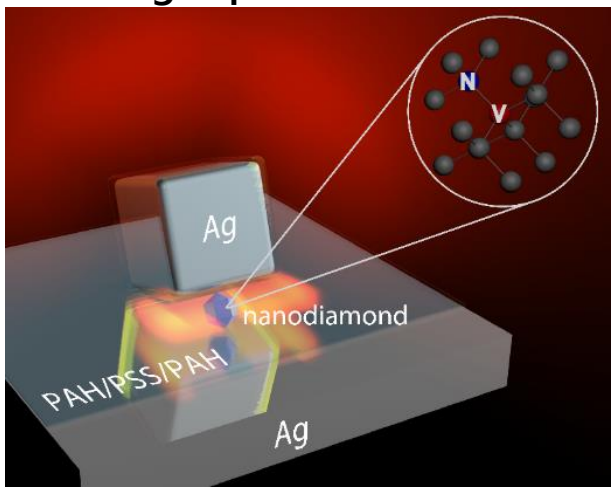
Quantum & quantum-inspired algorithms for computing speedup, optimization, data-analytics and machine learning (for wide range of scientific & business applications)

Research Spotlight Forum

To learn more: https://engineering.purdue.edu/PQC Email: PQC@purdue.edu (yongchen@purdue.edu);

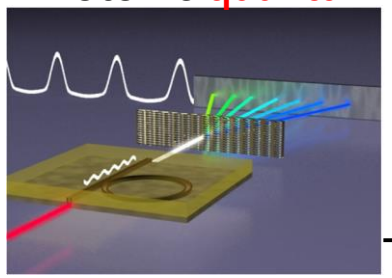
Representative Research on Quantum Photonics & Quantum Sensors @ PQSEI

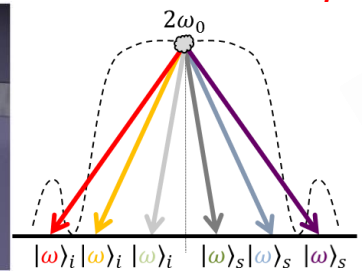
Ultrabright plasmon-assisted single-photon source

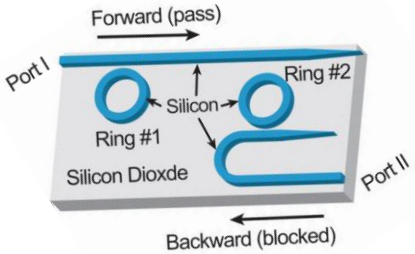


[Boltasseva & Shalaev] **Nanodiamond NV centers** coupled to low-loss Ag plasmonic cavities gives **world's brightest single-photon source** at room temperature [35M photons per second] Bogdanov et al. *Nano Letters* (2018)

Photonic quantum communication, computing, memory

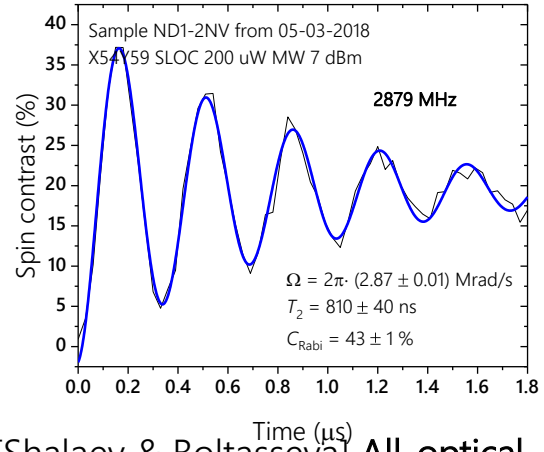




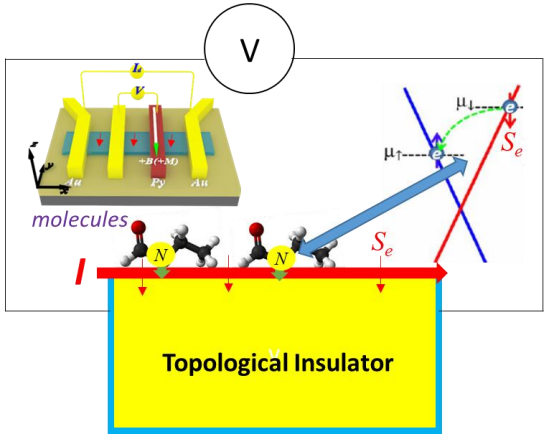


[Weiner] Pulse-shaping of photons (time/frequency domain); Photonic "qudits" (high-dimensional qubits) for quantum computing; e.g. Lukens et al. Phys. Rev. Lett. 112, 133602 (2014); Lu et al. Phys. Rev. Lett. 120, 030502 (2018); Optica 5, 1455 (2018). [Weiner/Qi/Hosseini] chip-based source of single & entangled photons; *Sandia collab: Paul Parazzoli (DARPA APhI -- Trapped-Ion Clock with photonic Technologies On Chip (TICTOC))*

Nano-scale magnetometer and NMR sensors



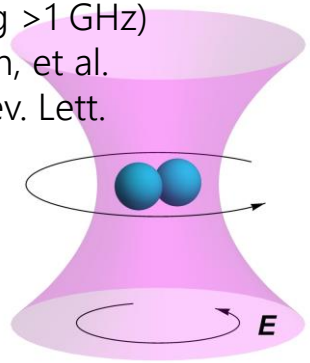
[Shalaev & Boltasseva] **All-optical** (based on NVs..)& other color-centers [also work by Li]



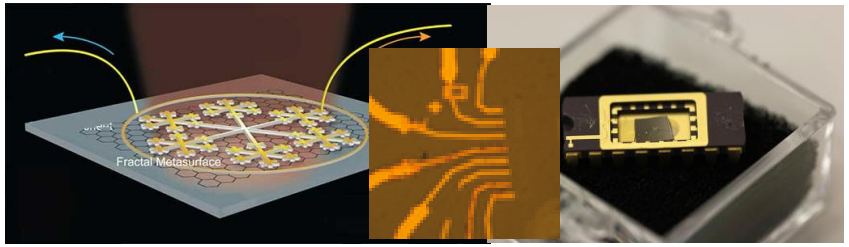
[Chen] **All-electrical** (based on topological insulators) Tian et al., Science Adv. (2017)

Torque and force sensing

With trapped nanoparticles -- **fastest nano-gyroscope!** (rotating >1 GHz) [Li]J. Ahn, et al. Phys. Rev. Lett. (2018)



Graphene-based photo/radiation-detectors



[Kildishev, Shalaev, Boltasseva, Chen] Enhanced **Graphene-Fractal Metasurface Photodetector** Fang et al. Nano Lett. (2017); [Chen] **Sensing radiation (visible to X-rays/gamma) with graphene transistor** Sarker et al., Nature Nanotech. (2017); Cazalas et al. Appl. Phys. Lett. (2015)

More information: Yong P. Chen (Director, PQSEI; yongchen@purdue.edu)

Hybrid Integrated Quantum Photonic Lab

Chip-based quantum memory; e.g. Jiang et al. Opt. Lett. 43, 20, 4973 (2018)

PI: Mahdi Hosseini
Assistant Prof. of ECE
Purdue University

Objective:

- Integration of atoms and ions with silicon photonics for realization of strong light-matter interactions on chip

Applications:

- Quantum sources and memories for quantum communication
- Photonic logic operation for quantum computation

Approach:

- We investigating cooperative coupling of rare earth ions with photons enhanced by the plasmonic and dielectric mode confinement to realize strong linear and nonlinear light-atom interactions on a hybrid scalable platform.
- We take the loss in the plasmonic structures to our advantage while relying on the strong light confinement to controllably engineer the quantum interactions.
- We work to achieve

1. Superradiance of ions in Si photonic structures for photon generation
2. Integration of rare earth crystals with Si photonics for quantum light storage near the telecomm wavelength
3. Implementation of a hybrid dielectric-plasmonic platform for optical storage and processing

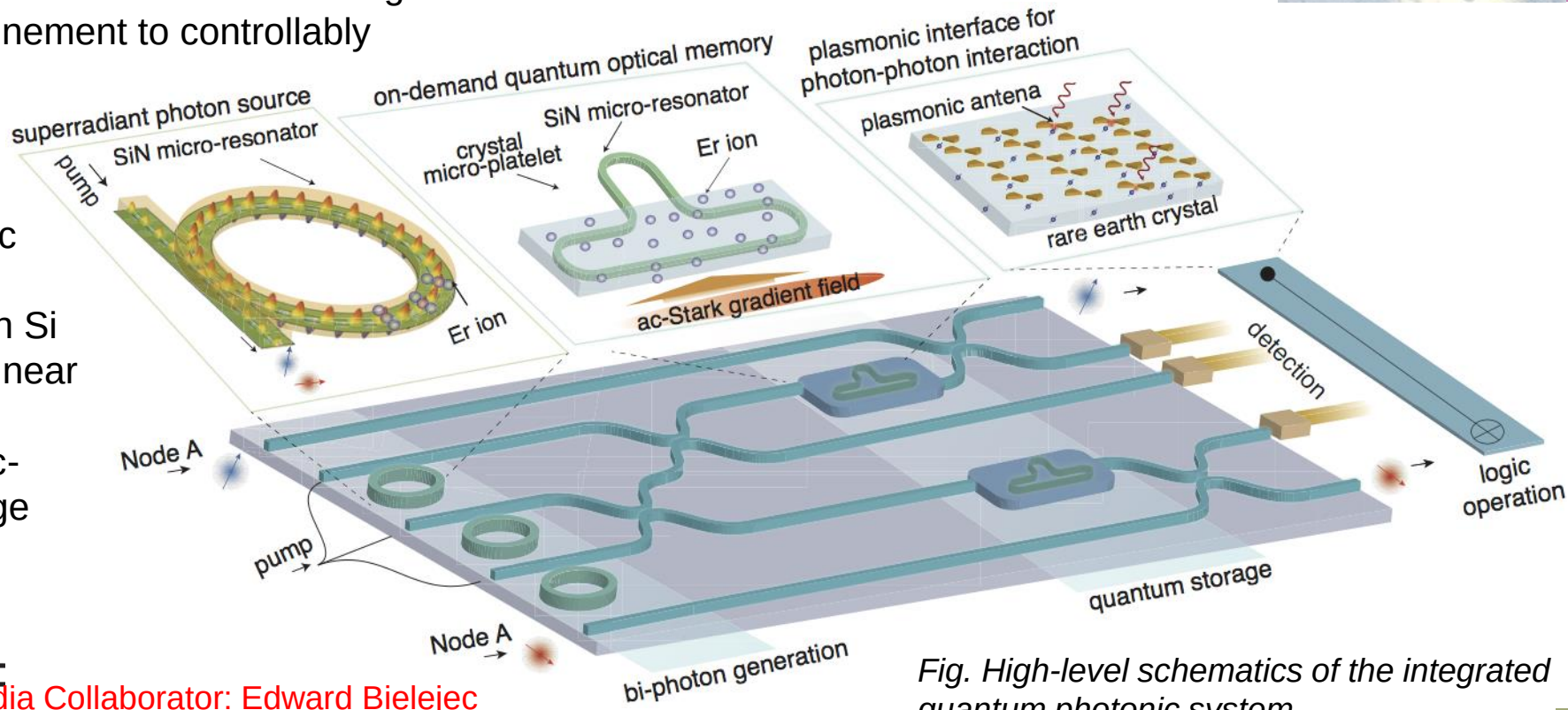
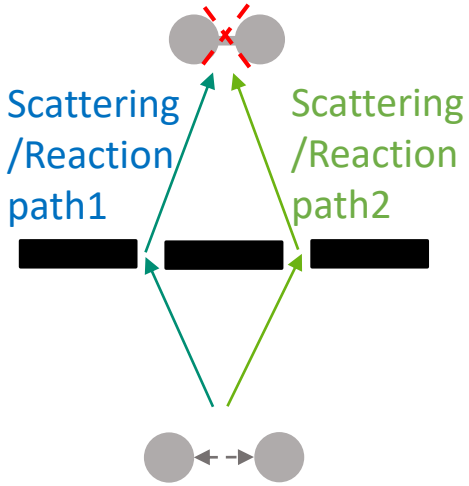


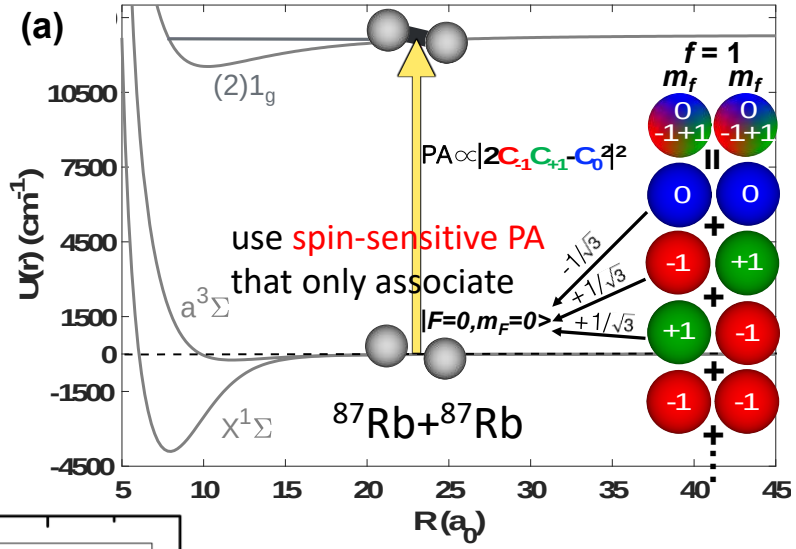
Fig. High-level schematics of the integrated quantum photonic system

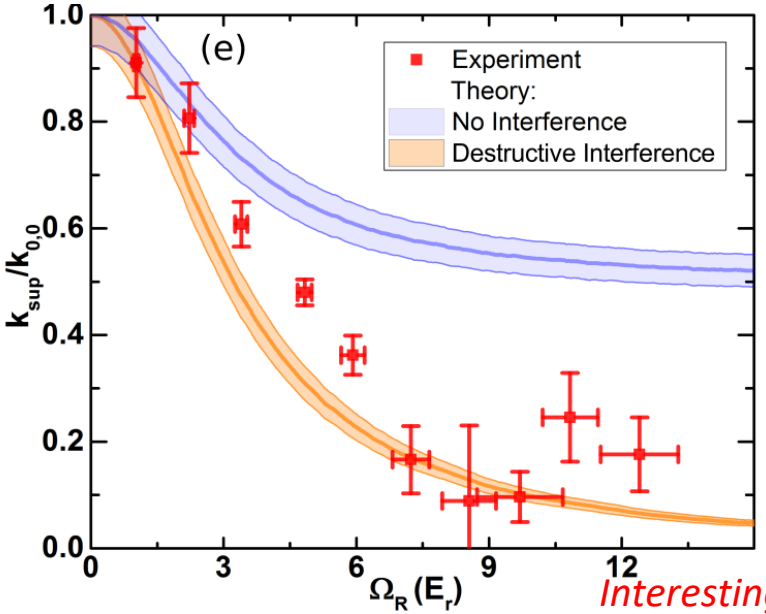
Sandia Collaborator: Edward Bielejec

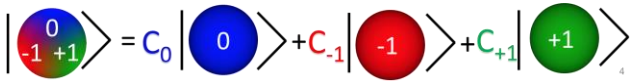
Quantum Control and Quantum Chemistry

"Quantum chemistry interferometry" using
reactants (atoms) in (spin) *quantum superposition* states









Destructive interference shuts-off the reaction!

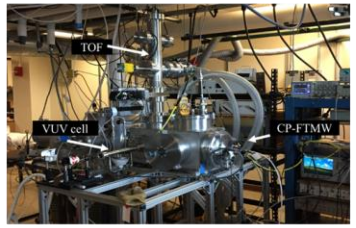
David B. Blasing, ..., Qi Zhou, Yong P. Chen, "Observation of Quantum Interference and Coherent Control in a Photo-Chemical Reaction", Physical Review Letters 121, 073202 (2018)

:orum

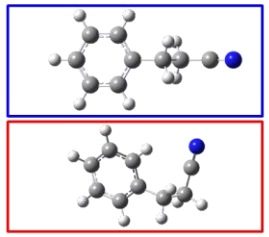
Interesting to explore quantum chemistry/catalysis?

Encoding and Read-out of Quantum Information in Molecular Rotational Energy Levels

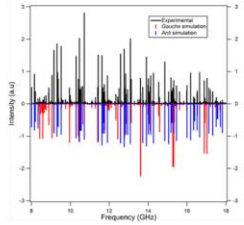
Tim Zwier



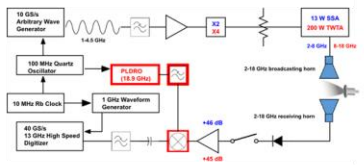
Chirped-pulse Fourier Transform Microwave (CP-FTMW) Chamber



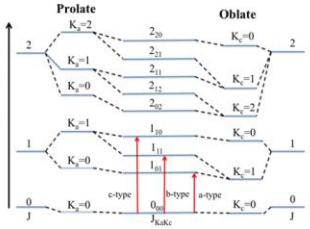
2 conformers of phenylpropionitrile



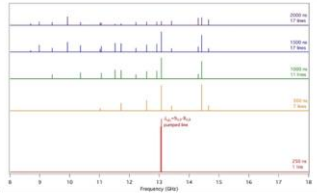
CP-FTMW spectrum of phenylpropionitrile



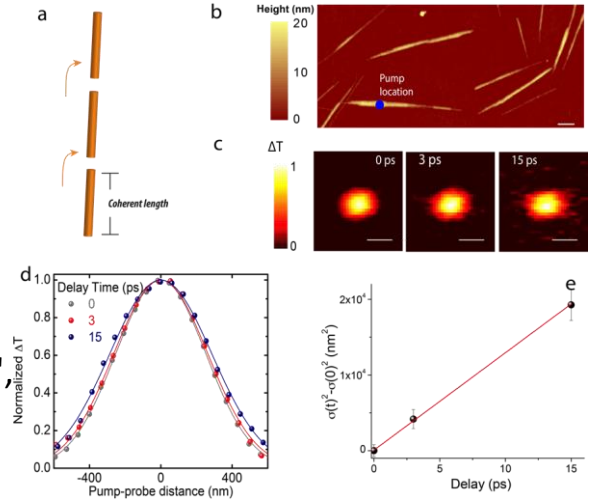
CP-FTMW Electronics 2-18 GHz frequency range



Model rotational energy levels of an asymmetric top



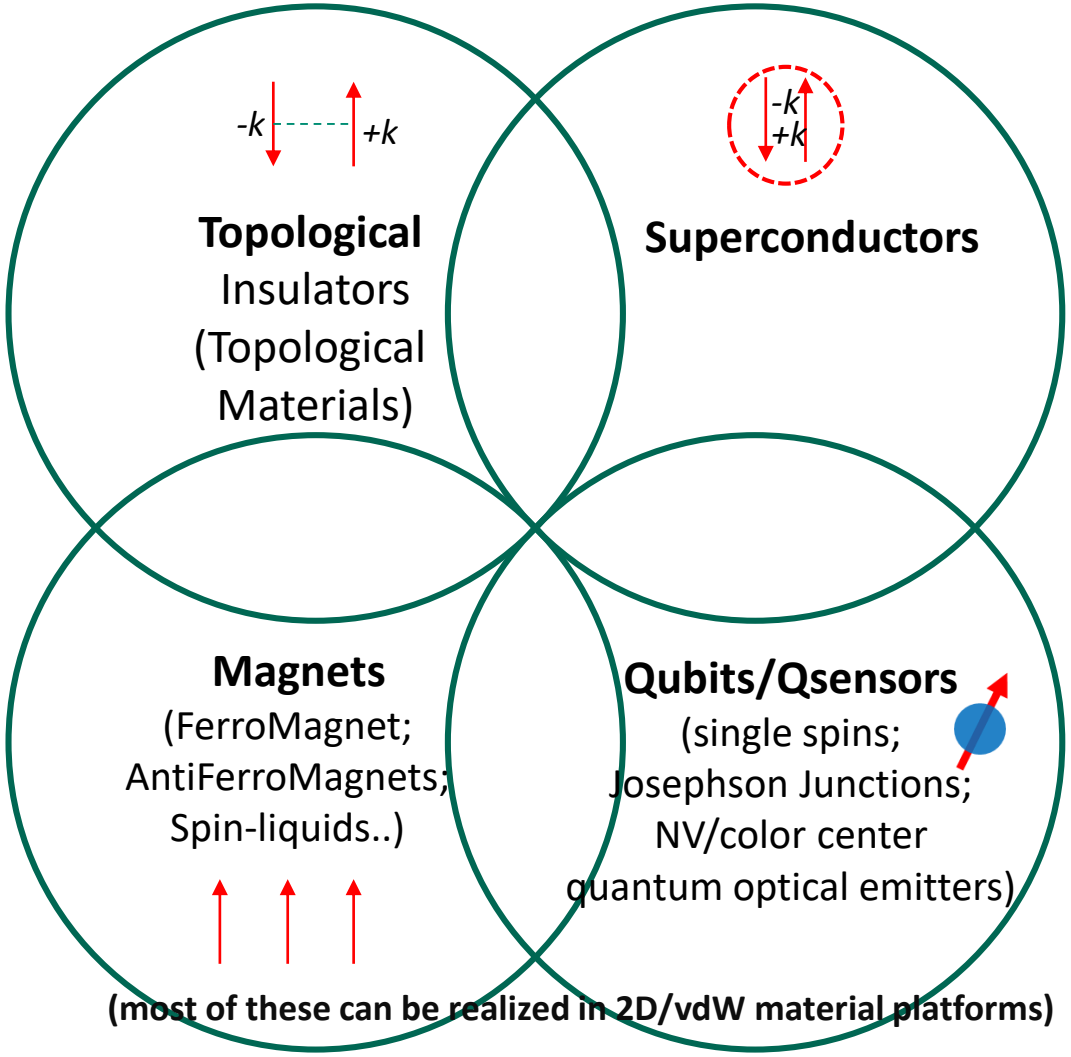
Multi-resonant coherence effects as a function of the number of Rabi cycles

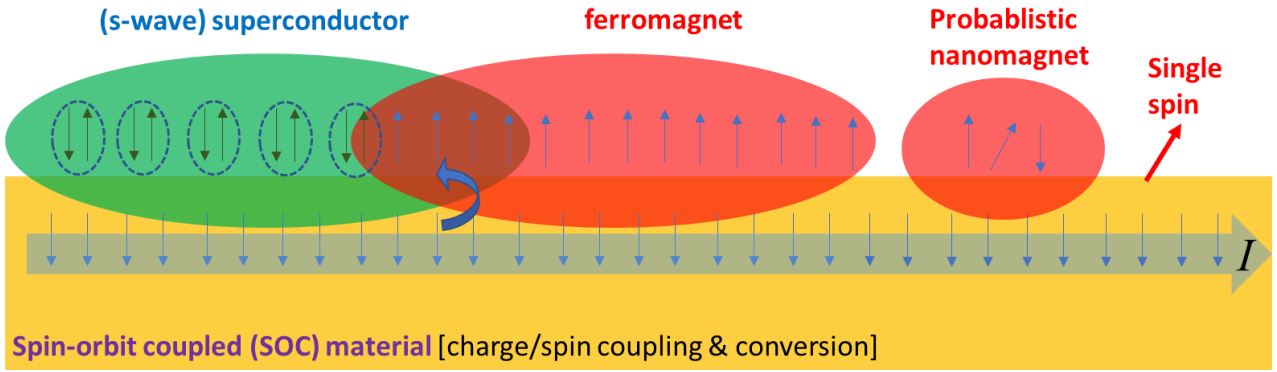


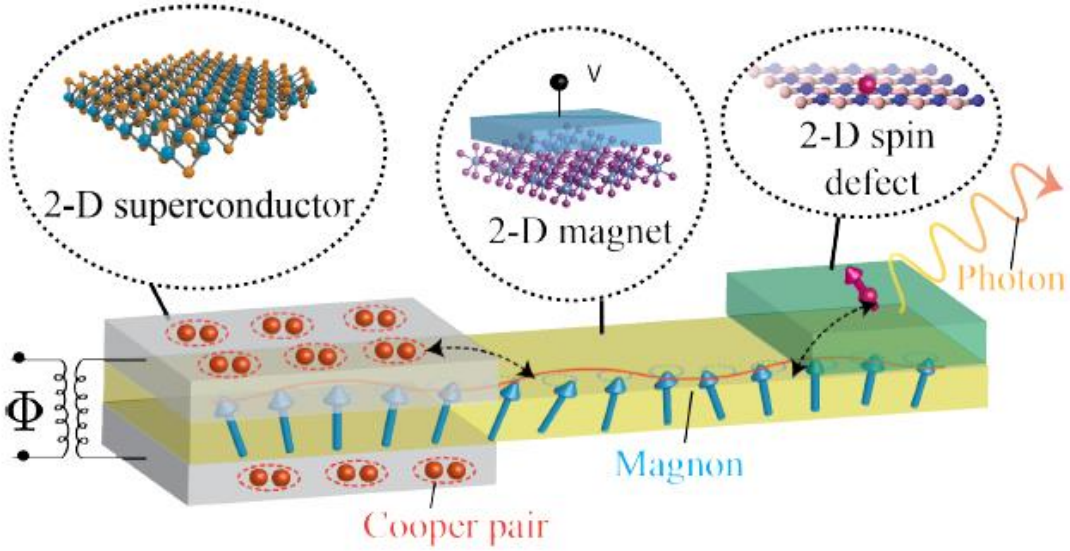
Coherent exciton transport in molecules (important for photosynthesis, solar cells...)

Libai Huang

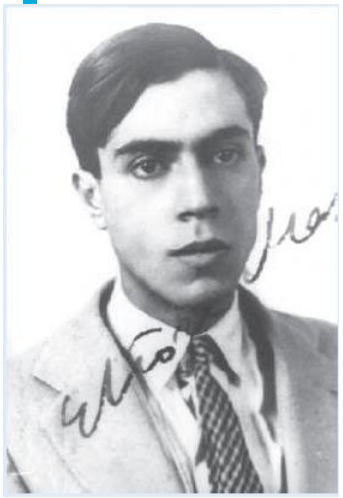
Hybrid ("Spintronic") Quantum Materials Platform for Quantum Information [Spintronics-Superconductivity-Quantum Photonics]







Topological Superconductivity & "Majorana fermions"



Majorana (fermion)

- **Neutrino?**
- **Supersymmetric partner**

e.g. of *photon: photino*

…

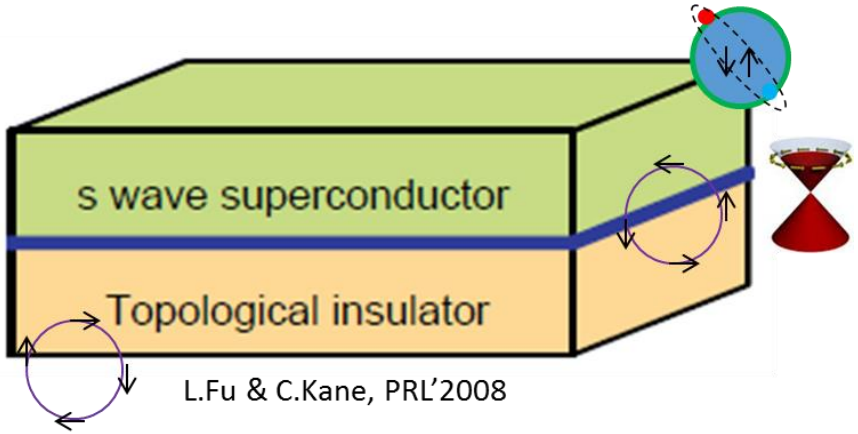
WIMPs (dark matter) ?…

PRL **100**, 096407 (2008)

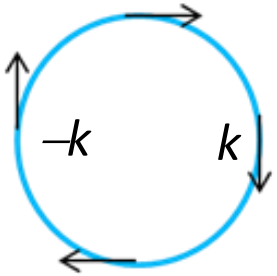
Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator

Liang Fu and C. L. Kane

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA



L.Fu & C.Kane, PRL'2008

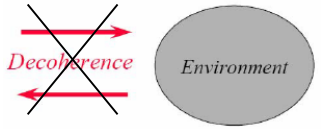


Spin-helical ("spinless") fermion + s-wave SC

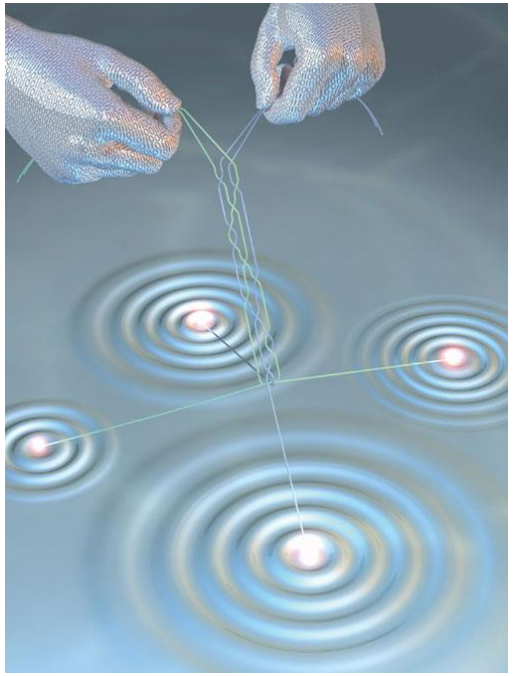
$$2\uparrow_{-k}\downarrow_{k}=(\uparrow_{-k}\downarrow_{k}+\downarrow_{-k}\uparrow_{k})+(\uparrow_{-k}\downarrow_{k}-\downarrow_{-k}\uparrow_{k})$$

→ **p-wave ($p_x \pm ip_y$) superconductor**

→ **Majorana "fermion" (anyon)**

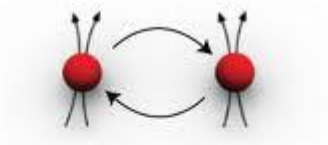


Topological quantum computing



G. Collins, Scientific American '06

Non-Abelian statstics (2D)



$$\Psi_{12} \neq e^{i\phi}\Psi_{21}$$

Other "Majorana" systems:
Fractional quantum Hall [5/2?]
p-wave superconductor
[Sr_2RuO_4?...]
topological superconductor
[$Cu_xBi_2Se_3$?]
s-wave SC/semiconductor
(w/t spin-orbit) [InSb,...]
cold atoms & molecules ……

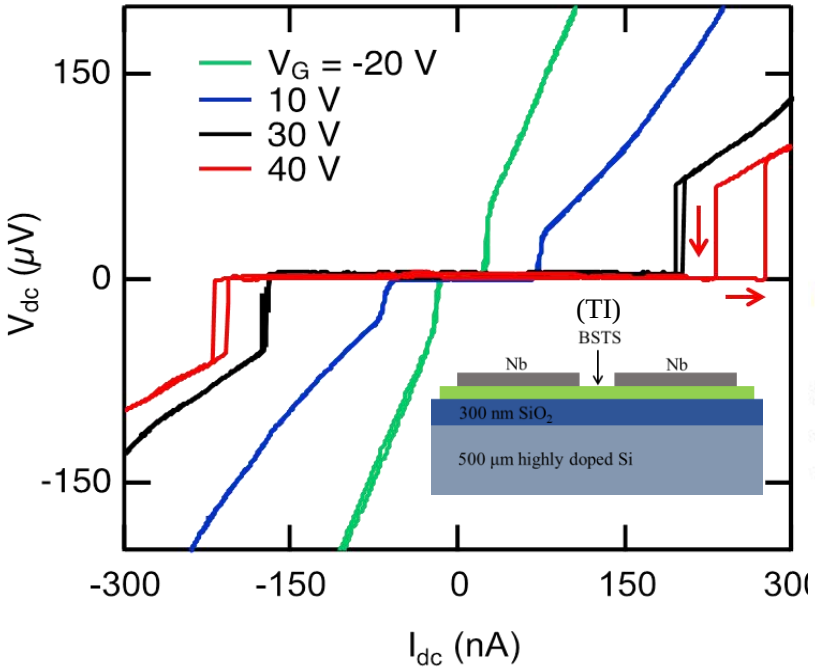
SC/TI/SC Josephson Junctions & SQUIDs –-probe topological superconductors/majoranas

Phase-sensitive measurements: can apply to other "unconventional" or "topological" superconductors

Luis A. Jauregui & M. Kayyalha et al. Appl. Phys. Lett. **112**, 093105 (2018);

M. Kayyalha et al. **PRL** 122, 047003 (2019)

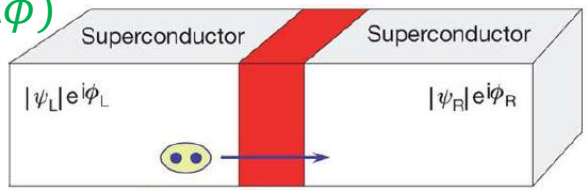
Gate-tunable supercurrent

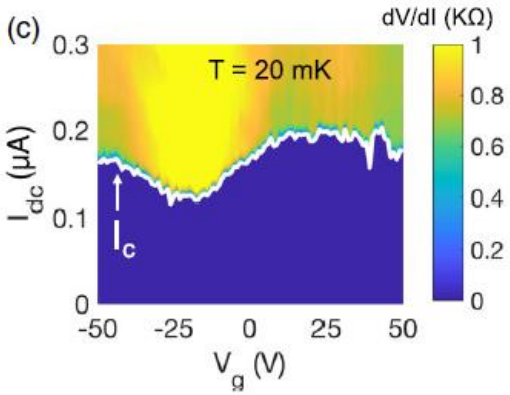


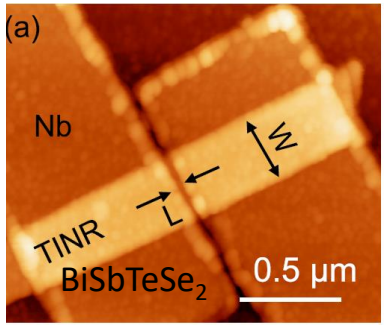
$$I = I(\Delta\phi) = I_c \sin(\Delta\phi)$$

(simplest /conventional)

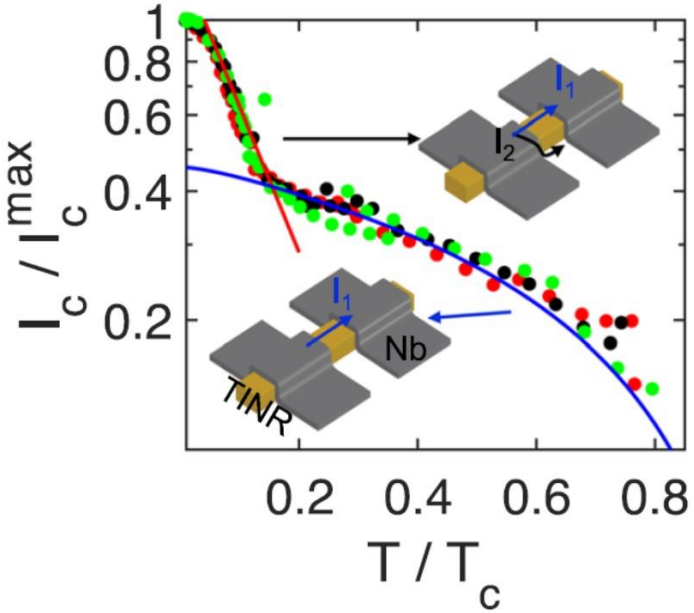
Josephson junctions





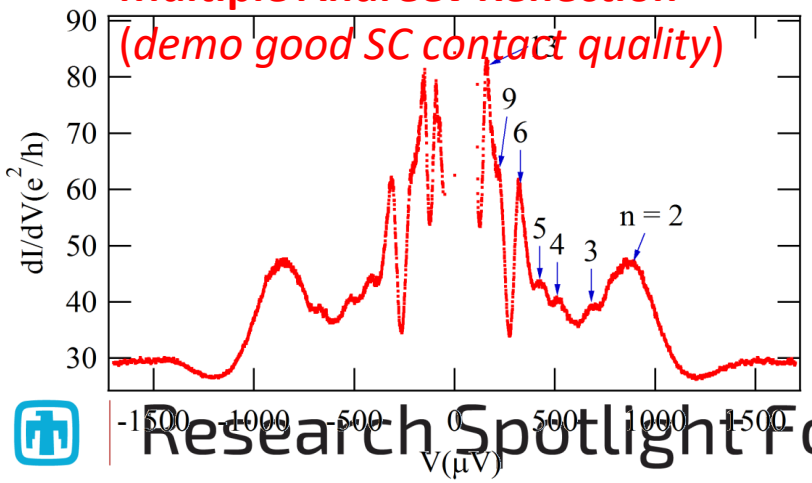


Anomalous T-dependence of Ic

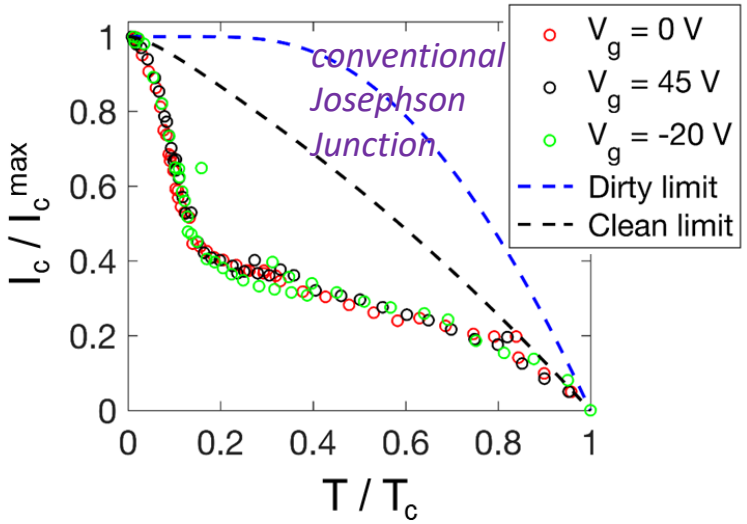


Multiple Andreev Reflection

(demo good SC contact quality)



Morteza Kayyalha (→ PSU)

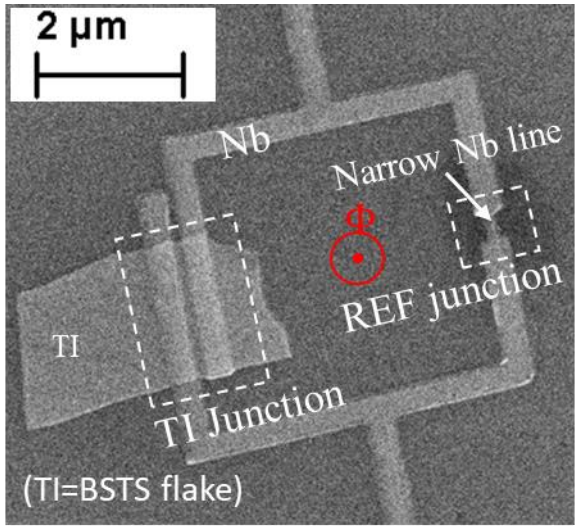


collaborators: L. Rokhinson (Purdue) et al.

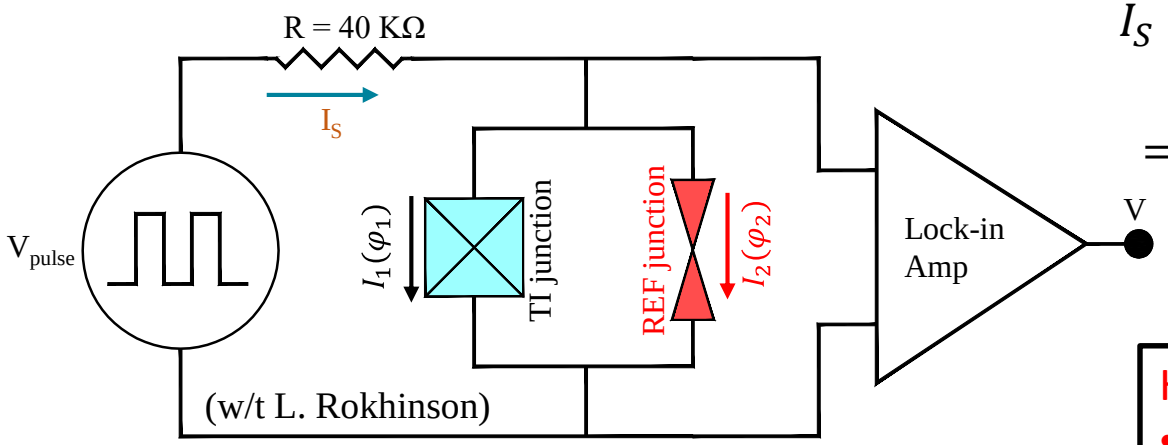
Measurement of Current-Phase Relation (CPR) of S/TI/S

M. Kayyalha et al. submitted'2018; arXiv:1812.00499

----- *"two pathway interference for supercurrent (cooper pairs)"*



Technique: "asymmetric **SQUID**" [e.g. Rocca et al. PRL'07]



$$I_S = I_{C2}\sin(\varphi_2) + I_1\left(2\pi\frac{\Phi}{\Phi_0} + \varphi_2\right)$$

$$\Rightarrow I_{CS}(\Phi) = I_{C2} + I_1\left(2\pi\frac{\Phi}{\Phi_0} + \frac{\pi}{2}\right)$$

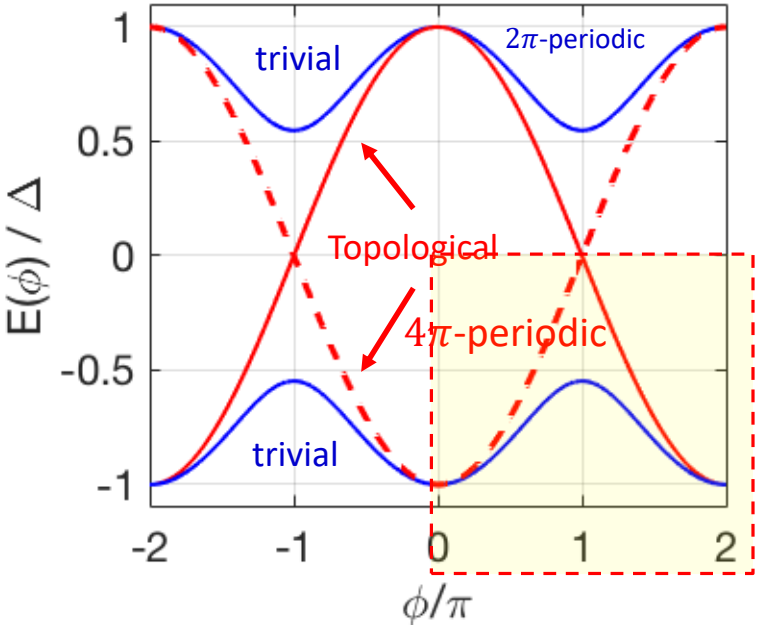
$$(I_{C2} \gg I_{C1})$$

Highly-skewed (non-sinusoidal) CPR!

- Low/zero energy ABS ($\varphi = \pi$)?
- Topological SC?

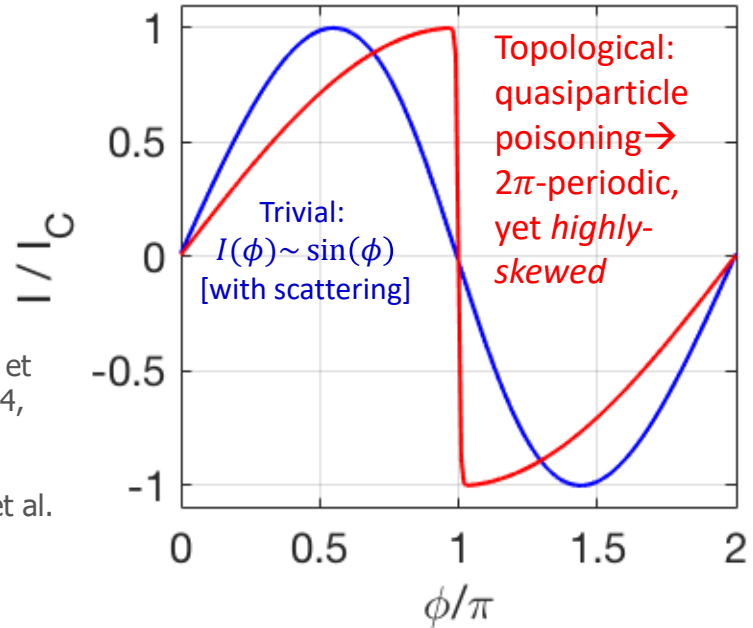
Andreev bound state (ABS) spectrum

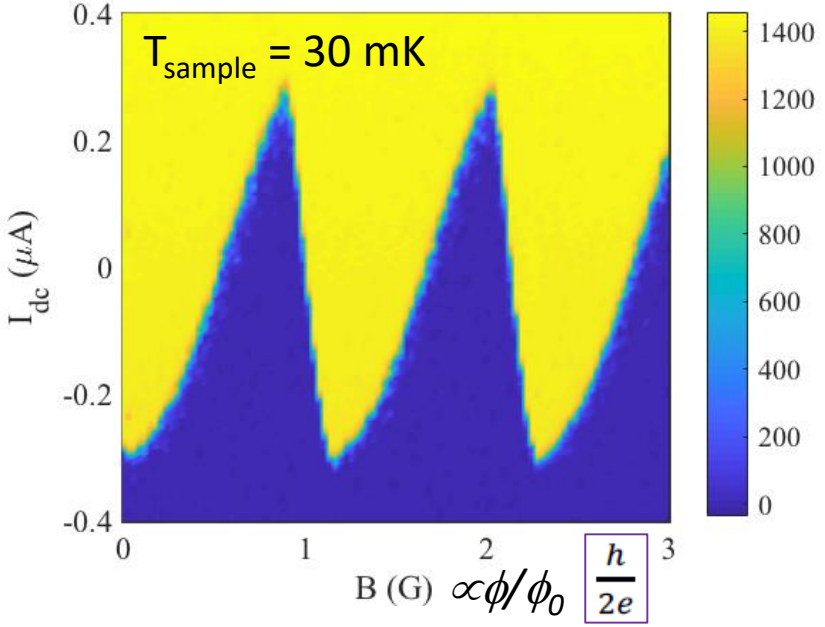
$$\frac{\partial E(\phi)}{\partial \phi} \rightarrow I(\phi)$$



e.g. Peng et al., PRB 94, 085409 (2016); Golubov et al. RMP 76, 411 (2004)

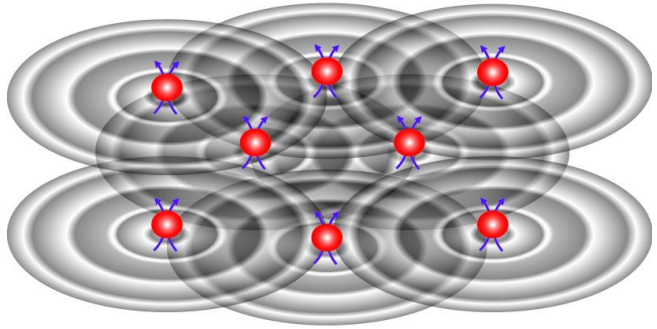
Caution: highly-ballistic junction can also gives skewed CPR





Current major platforms (physical systems) for Majorana & Topological QC

Fractional quantum Hall (FQH) States
[e.g. v=5/2 & related FQH states?]

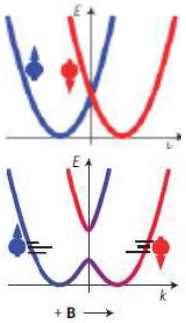


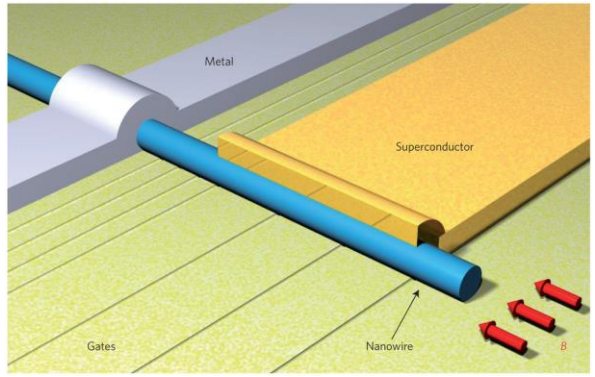
challenges:

- *Complex physics* – strongly interacting & correlated many-body states
- Need *ultraclean (high mobility) samples*
- *Ultralow temperature (mK) & high B field*

(pursued at Microsoft Station Q, etc.)

Spin-orbit-coupled semiconductor Nanowires [e.g. InSb, InAs] **+Superconductor (SC)**





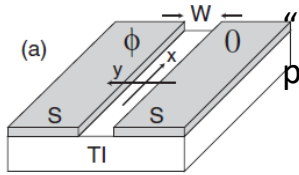
challenges:

- *Difficulty of control and fabrication* with 1D nanowires (NW) & NW-network [however: recent work turns back to 2DES]
- *Need high B field* to drive NW into TI-like state and then induce majoranas (extension/variant of Fu-Kane proposal)
- Spin-helical band/transport not shown (exp)

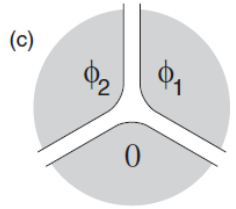
Advantage: well-developed semiconductor (e.g., MBE) based materials/devices/technology …

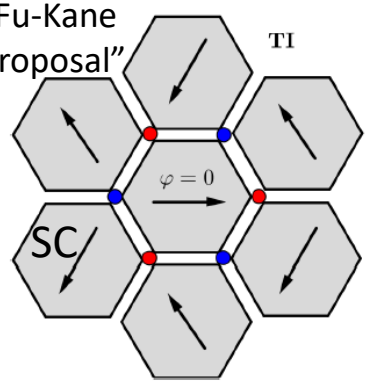
Manfra/Csathy/Rokhinson
(theory)Biswas/Lyanda-Geller

Topological insulator (TI) + Superconductors (SC)



"Fu-Kane proposal"





Advantages:

- 2D/*surface based devices* (SC islands on surfaces of TI): **easy fabrication** & scale-up
- Conceptually **simplest**, single-particle physics; **single particle spin-helical band/transport well established**
- No B field or only moderate B fields involved

Challenge: "less friendly" materials (?)

Chen/Rokhinson

Potential Sandia Collaborators: R.Lewis, W.Pan, J.Reno, M.Lilly…

A new frontier & practical application: "**quantum speedup**" of **optimization** problems

<using existing "small" quantum computer ("NISQ") or NISQ+classical computer to solve problems intractable today>

Connection with Krannert school & data-science intiative..

- Logistics Management
- Supplies Chain Management
- Network management
- Fault Diagnostics
- Software/electronics validation/verification
- Artificial Intelligence/Machine Learning
- Blockchain?…
- "post-quantum encryption"
- ….

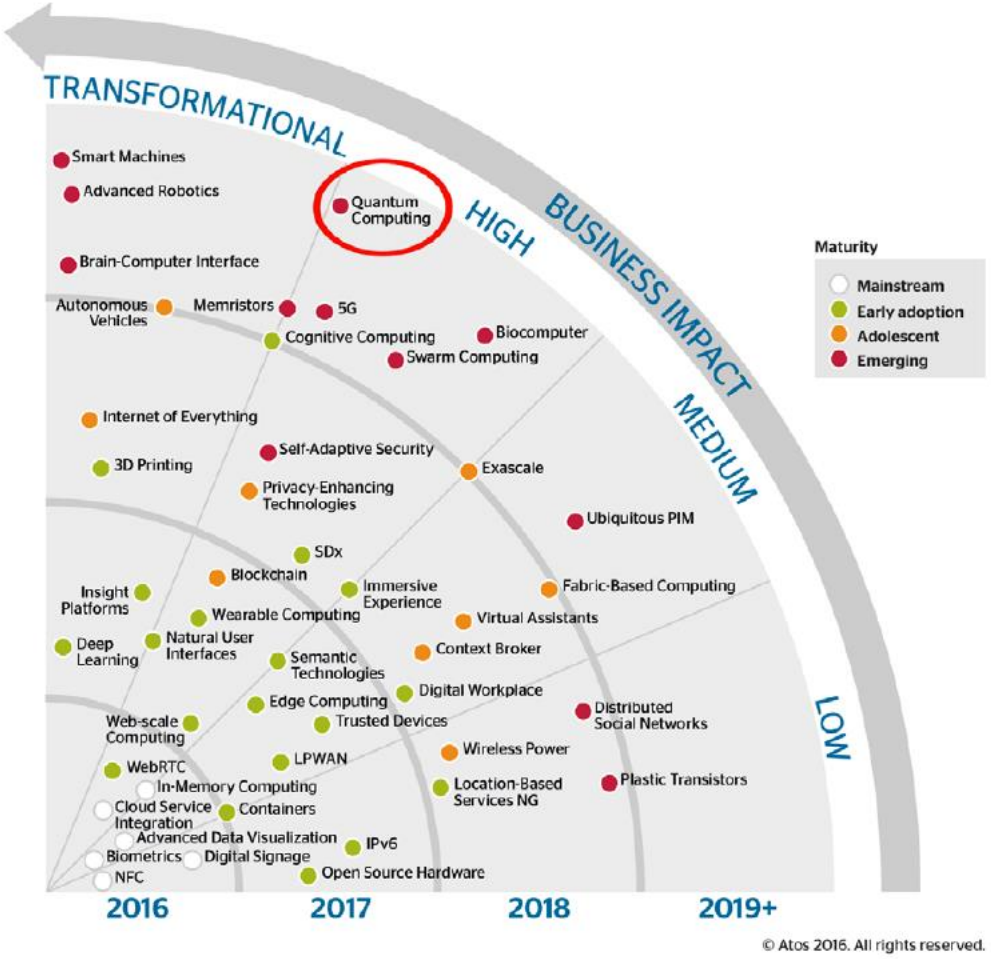


Figure 2.1: The technological landscape and impact on business / *Atos, 2016*

https://www.uidp.org/publication/catalyzing-industry-university-collaboration-in-quantum-technologies-workshop-report/

<R.Srivastava et al. NQIT user team report>

(PQSEI) [previously Purdue Quantum Center]

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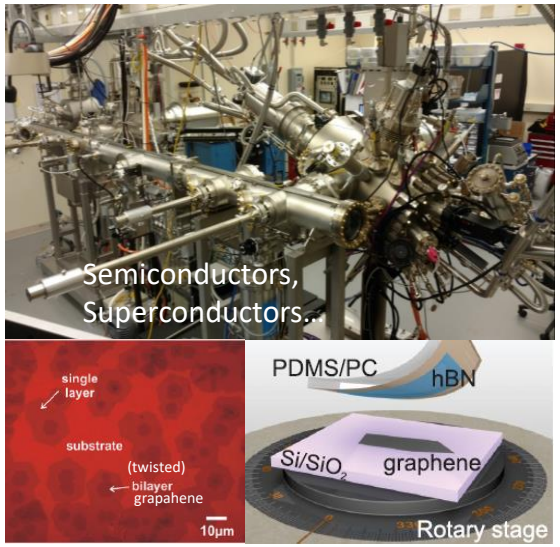
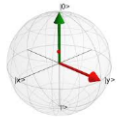
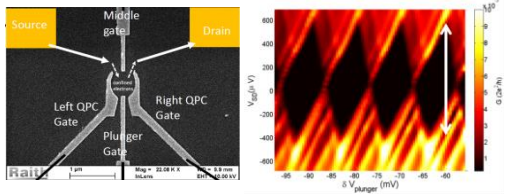
Quantum Materials



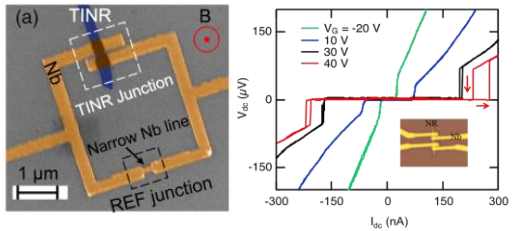
Quantum Devices



Quantum Dots

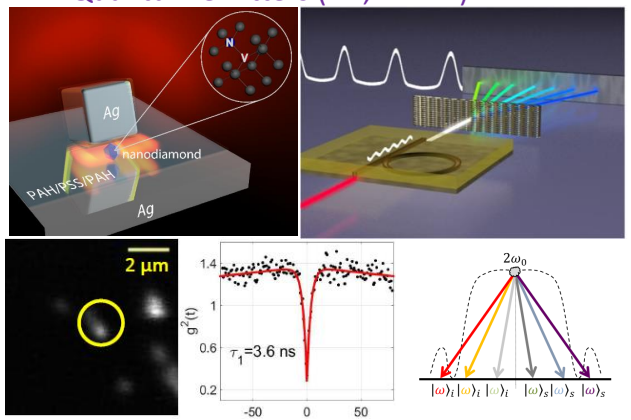


Josephson Junctions/SQUIDs



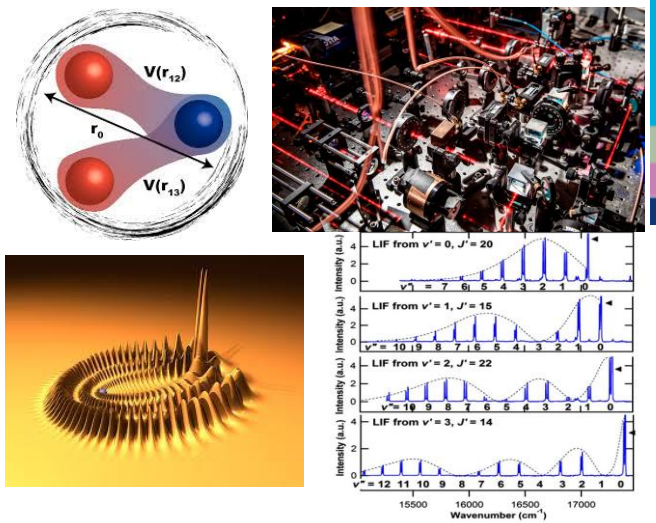
Quantum Photonics

Quantum emitters (NV, h-BN..)

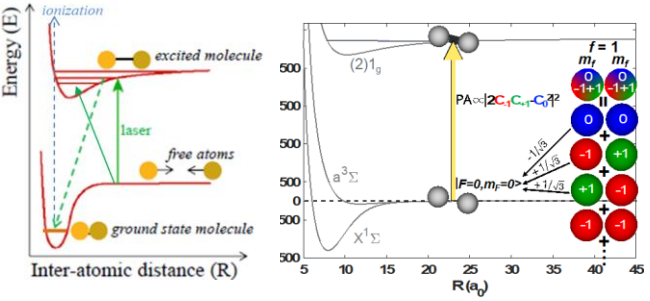


single photons & entangled photons

AMO Physics

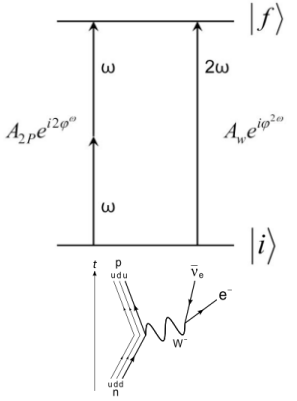


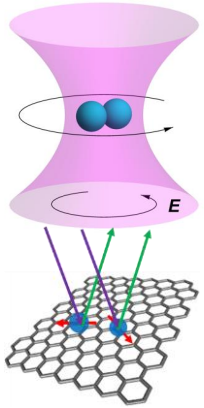
Quantum Chemistry



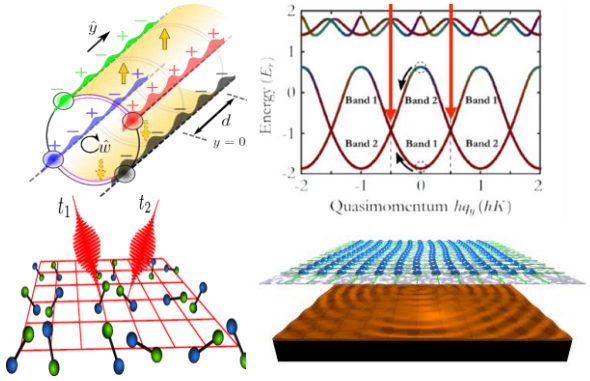
$$\left|\begin{smallmatrix}0\\-1\ +1\end{smallmatrix}\right\rangle = C_0\left|0\right\rangle + C_{-1}\left|-1\right\rangle + C_{+1}\left|+1\right\rangle$$

Quantum Control & Measurement

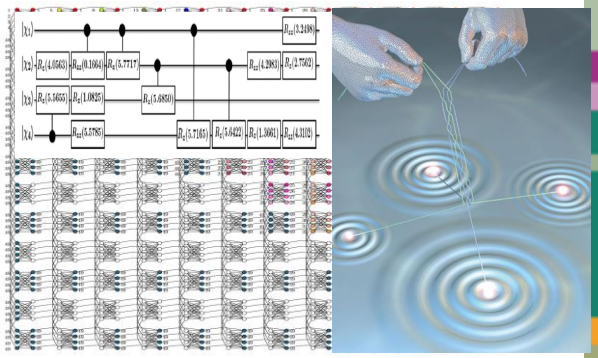




Quantum Simulation



Quantum Info/Computing/ Data/Machine Learning



Research Spotlight Forum

To learn more: PQC@purdue.edu (yongchen@purdue.edu); https://engineering.purdue.edu/PQC

Purdue Quantum Science & Engineering Institute

(PQSEI) [previously Purdue Quantum Center]

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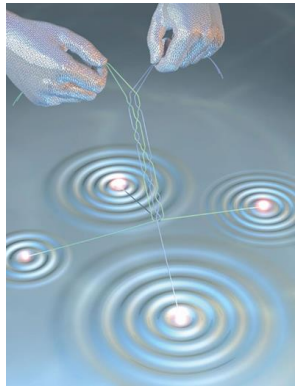
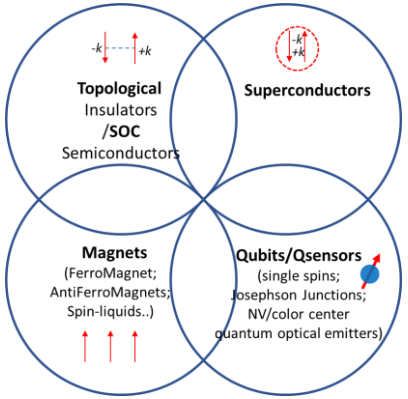
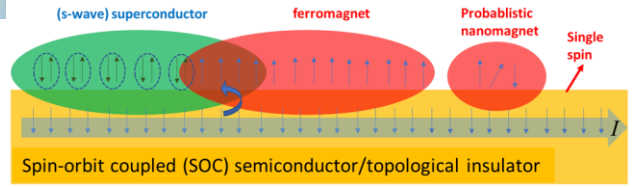
Some "big" questions & interdisciplinary research themes

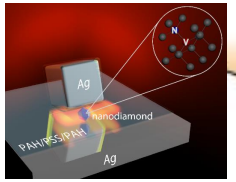
- *Can **topology** help store/process/**protect** (quantum) info?*

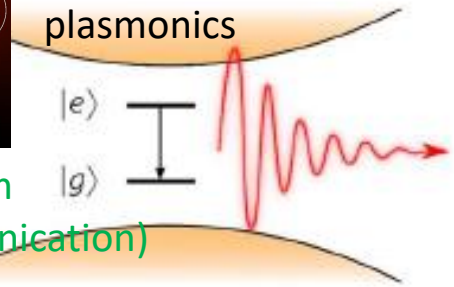




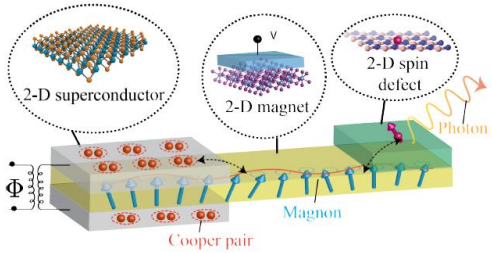


- *Can we **speedup** (light-matter interaction &) quantum operation to beat decoherence?*





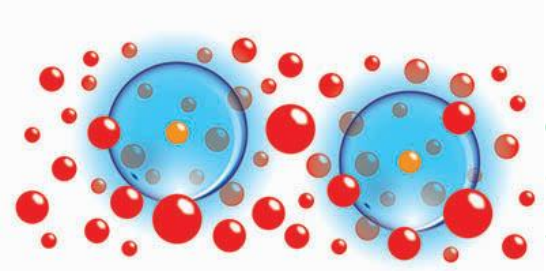
(***ultrafast*** quantum photonics/communication)



(platforms for most these themes: **hybrid quantum materials**)

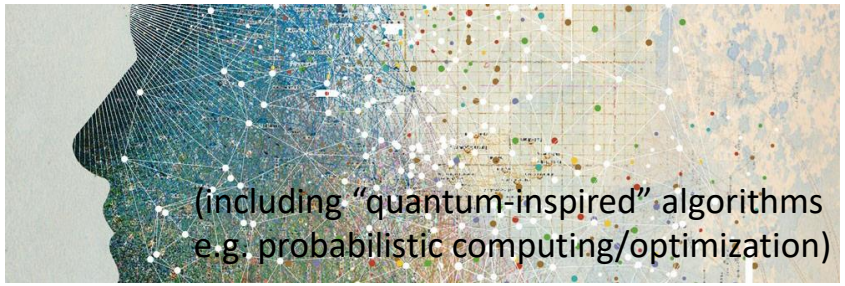
- *Using **quantum beam/bits** to **measure** quantum materials?*

- *"Using chemistry to study physics"*



(Novel **quantum chemistry/catalysis** of quantum systems/materials)

- *"Quantum **informatics** and **data analytics**" (speed up science & business?)*



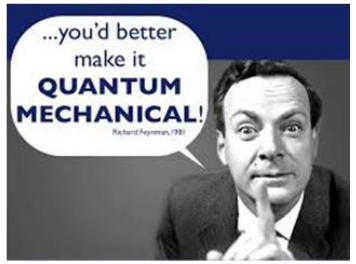
Research Spotlight Forum

To learn more: https://engineering.purdue.edu/PQC Email: PQC@purdue.edu (yongchen@purdue.edu);

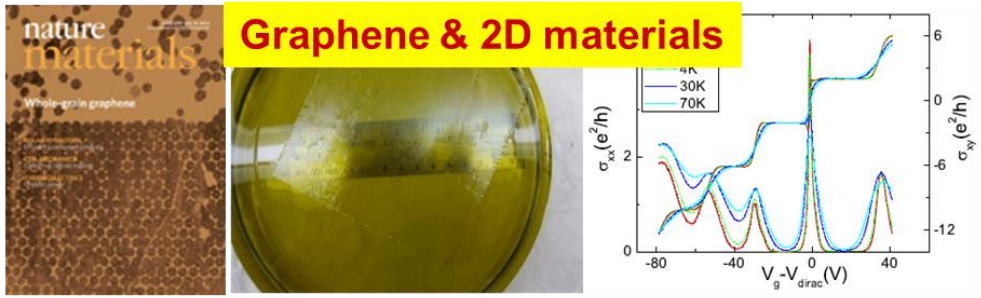
CURRENT WORK IN QUANTUM INFORMATION SCIENCES

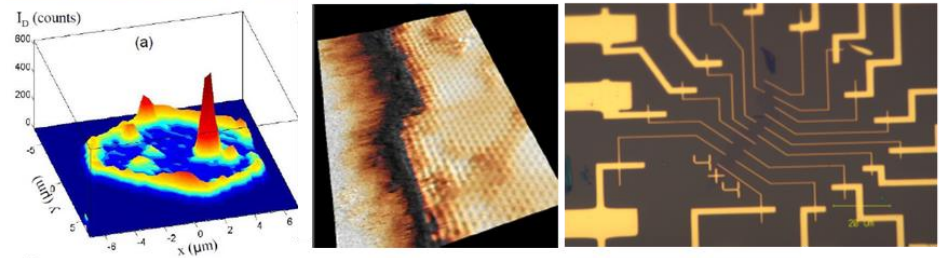
Postdoc Openings
(yongchen@purdue.edu)

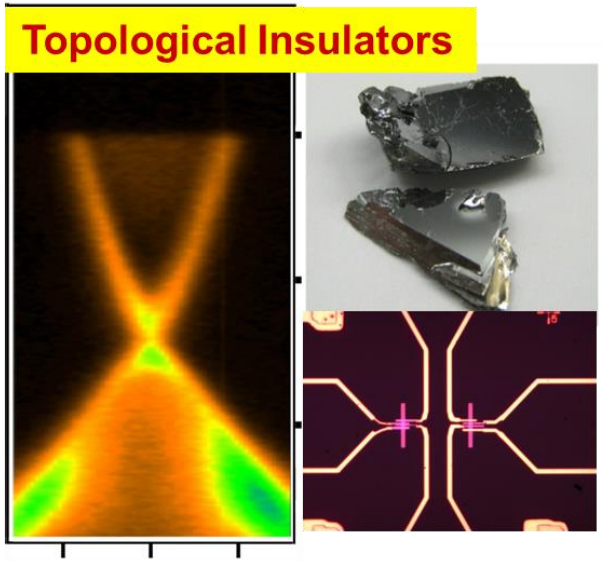
http://www.physics.purdue.edu/quantum *|QMD>=|physics>+|engineering>*

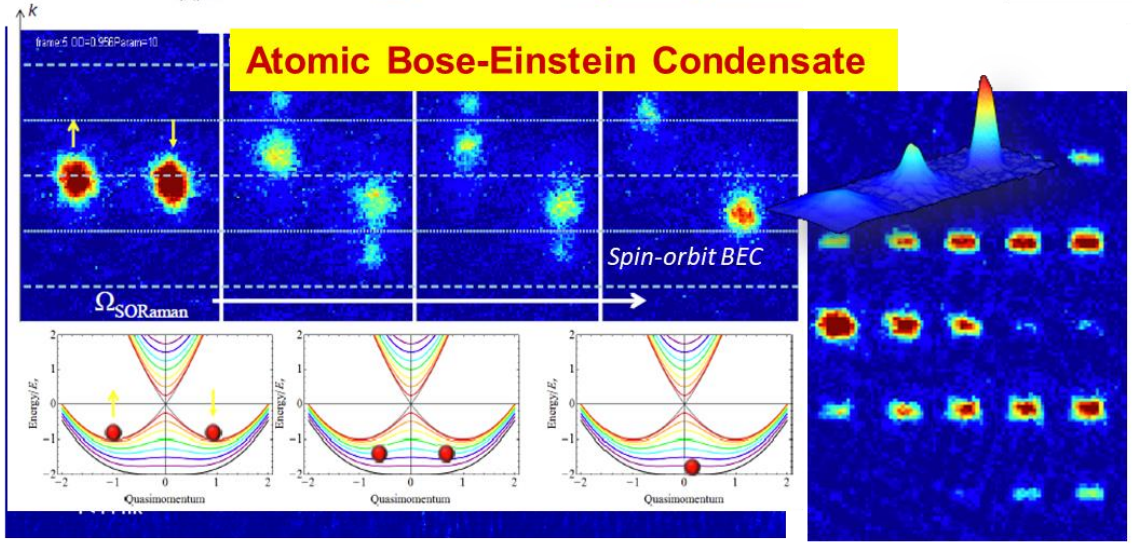


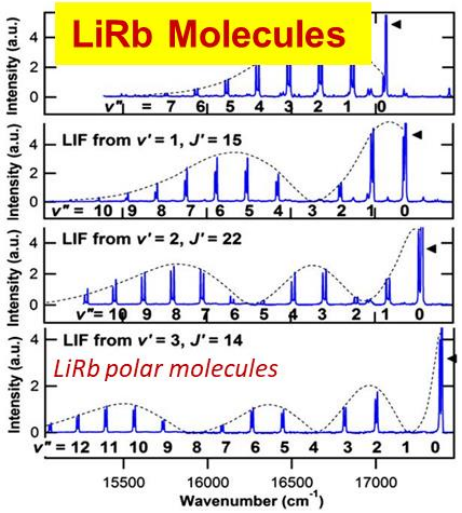
Quantum Synthesis
(➔novel Quantum matter)
+
Quantum Measurement & Devices
(& manipulation ➔new quantum technologies)











FUNDING SOURCES (current)

1. NIST, Quantum Electronic Metrology In Graphene Nanostructures (2013-2019)

2. NSF EFRI Newlaw: Topological Thermal Transport (2016-2020)

3. NSF (PHY): An Experimental Program On Spin-Orbit Coupled Bose-Einstein Condensates (2017-2020)

4. NSF (ECCS): Collaborative Research: Strain Based Devices For Switches And Memory Applications (2017-2020)

5. NSF (DMR): Eager: Enabling Quantum Leap: Electrically Tunable, Long-Distance Coherent Coupling Between Room Temperature Qubits Mediated By Magnons In Low-Dimensional Magnets (2018-2020)

[this project studies NV centers mediated by magnons on magnets]

6. DOE BES: Quantum Computing Algorithms And Applications For Coherent And Strongly

Correlated Chemical Systems (2018-2021)

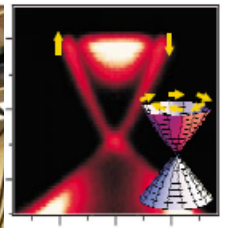
7. Lockheed Martin: Demonstration Of A Topological Insulator Based Coherence Battery (2018-2019)

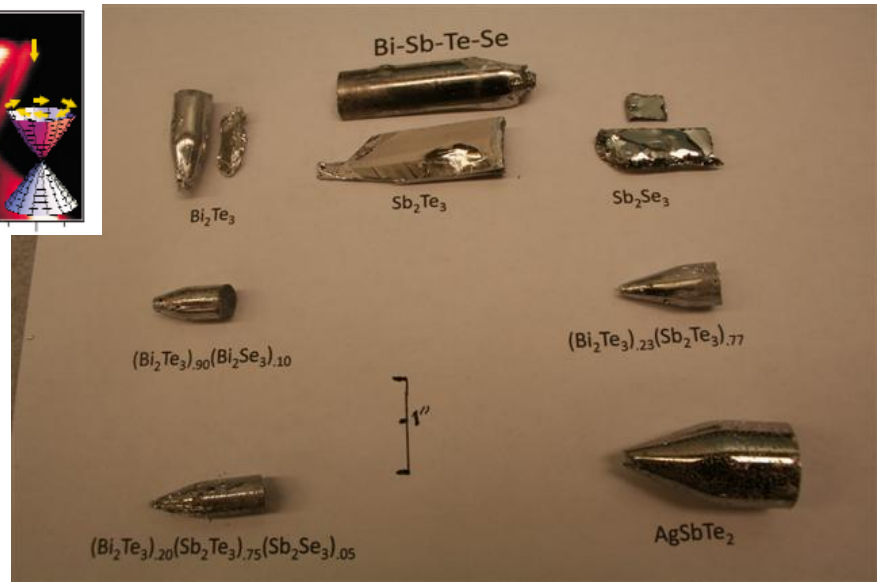
8. WPI-AIMR/JSPS(Tohoku Univ.): International Joint Research – Quantum Materials and Spintronics (2019-2020)

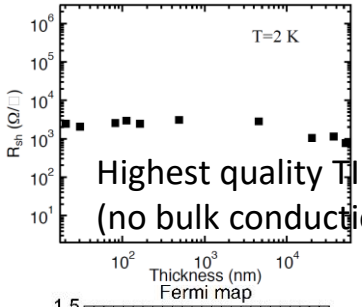
Making Quantum Materials

Interests:Topological/2D Materials for QIS Applications

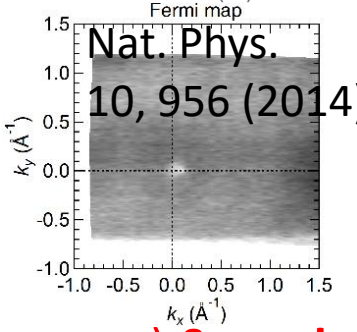
Topological insulators & related crystals (~150, https://www.physics.purdue.edu/quantum/purdueticrystal.php)



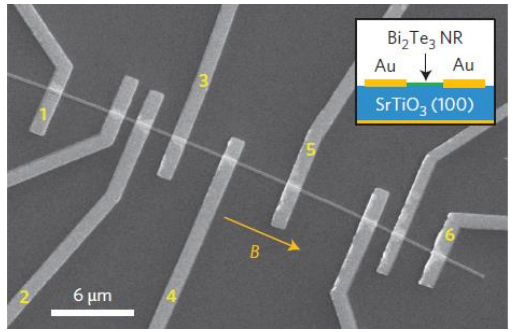




Highest quality TI crystal (no bulk conduction)

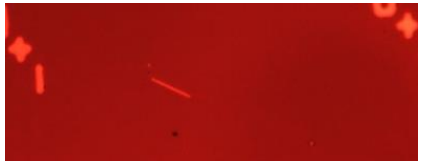


Nat. Phys. 10, 956 (2014)



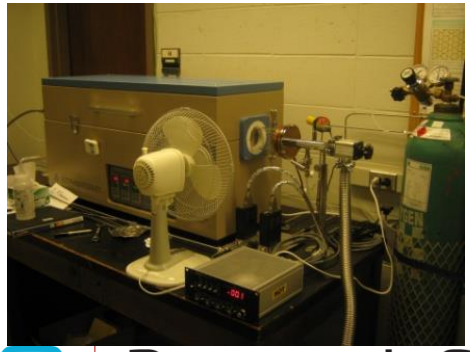
Nature Nano 11, 345 (2016)

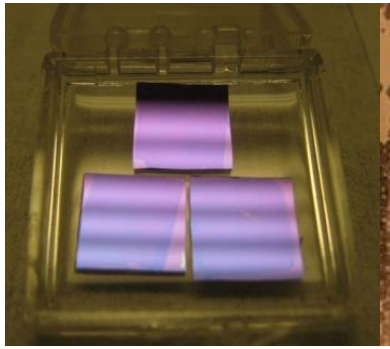
~2D flakes
& 1D nanoribons
(CVD & exfoliation)

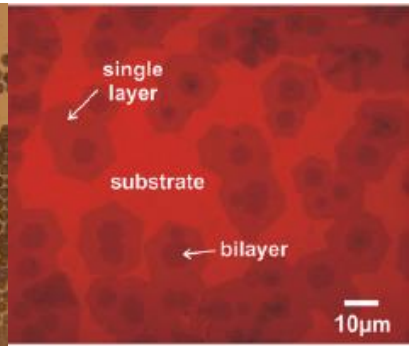


2D materials (graphene, TI, h-BN, TMDCs, magnets, superconductors..) & **stacked/twisted heterostructures**

by CVD & exfoliation/transfer

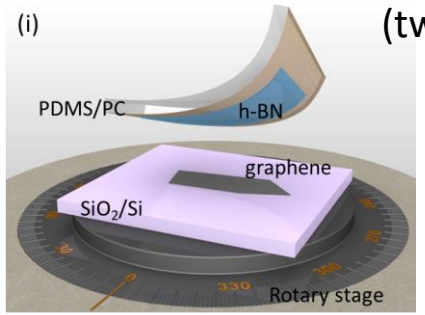




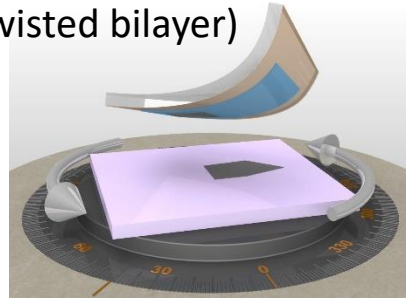


Nature Materials 10, 443 (2011)

Nano Lett. 13, 3594 (2013)



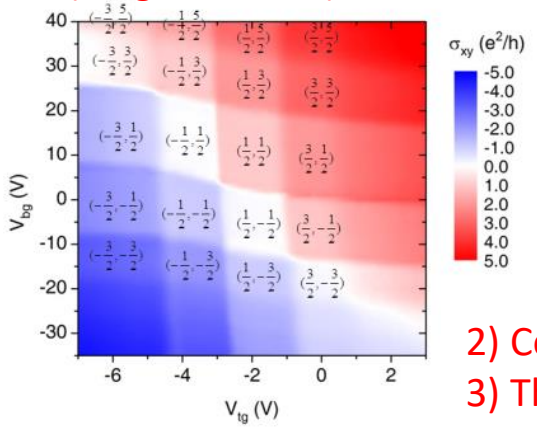
(twisted bilayer)



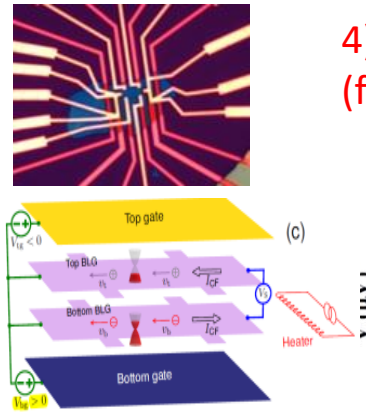
PRB 98, 035425 (2018)

Transport/devices [T~10mK to >300K; B to 10-18T @PU, 35-45T in magLab; with back/top/side/ion gate]

1) Charge transport (magneto/QHE)



Nature Comm. 7, 11434 (2016)

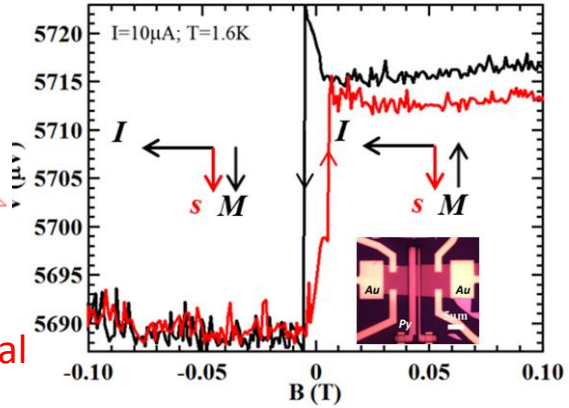


2) Coulomb drag

3) Thermoelectric/thermal

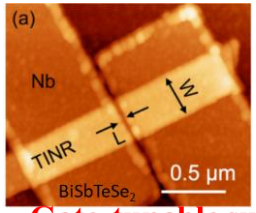
Nano Energy 40, 42 (2017)

4) Spin transport (ferromagnetic electrodes)

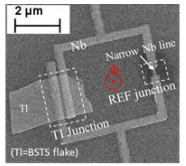


Sci. Rep. 5, 14293 (2015)

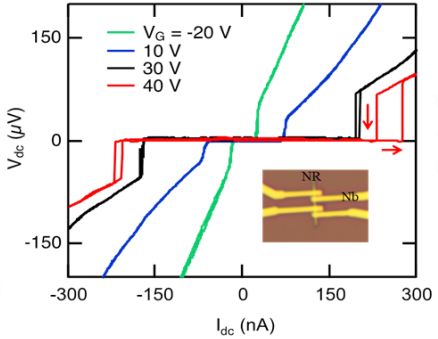
Science Adv. 3, e1602531(2017)



5) Josephson junctions & SQUID (superconducting electrodes)



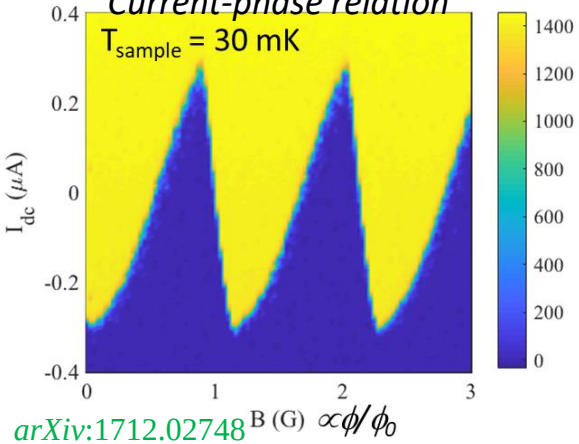
Gate-tunable supercurrent



APL 112, 093105 (2018); *arXiv*:1712.02748

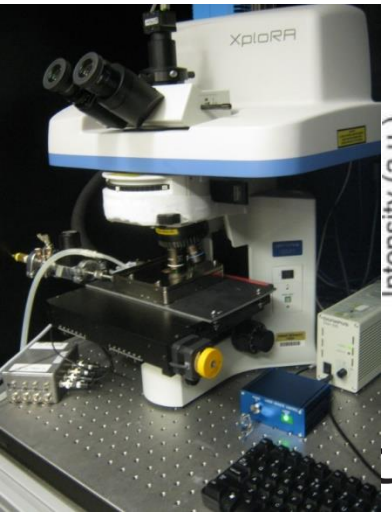
Current-phase relation

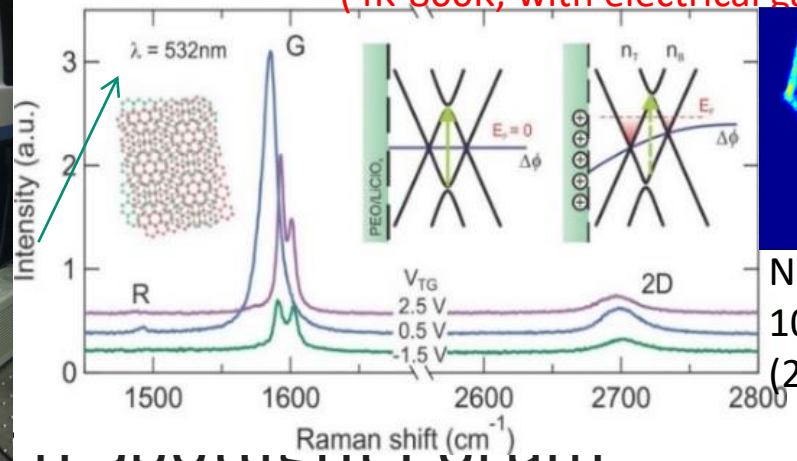
T_{sample} = 30 mK

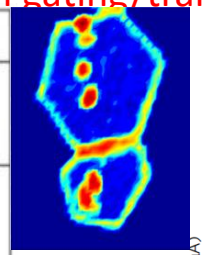


Optical/Optoelectronics

1) Raman/PL spectroscopy & mapping (4K-800K, with electrical gating/transport)

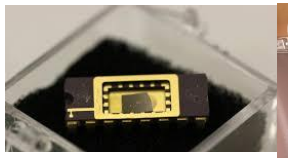


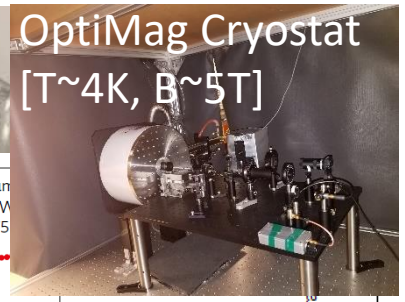




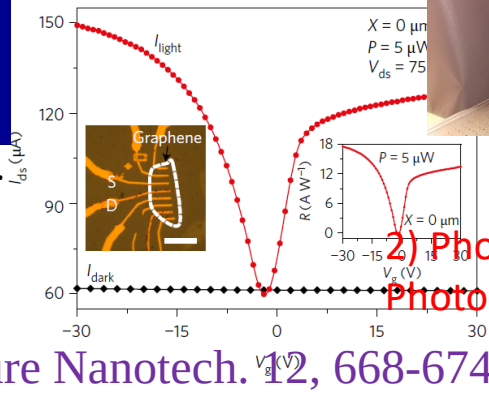
Nat. Mat. 10, 443 (2011)

Nano Lett. 15, 1203 (2015)





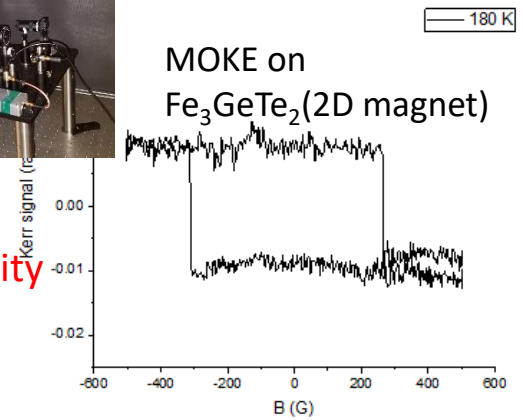
2) Photoconductivity Photocurrent…



Nature Nanotech. 12, 668-674 (2017)

3) Kerr/Faraday Rotation (micro MOKE)

MOKE on Fe_3GeTe_2(2D magnet)



Interests:Topological/2D Materials for QIS Applications

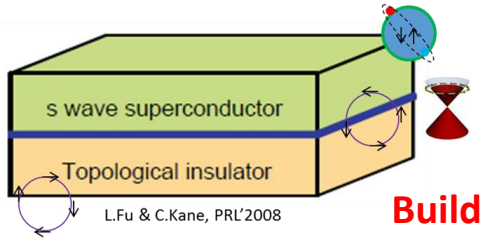
- **TI-based "majorana"/topological qubits**

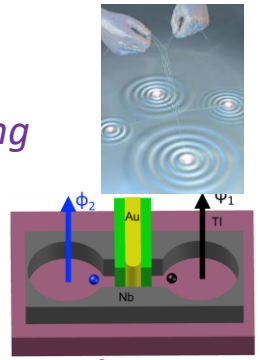
(demo "Fu-Kane proposal" etc.)

TI + (2D) superconductors

Majorana/non-Abelian anyons

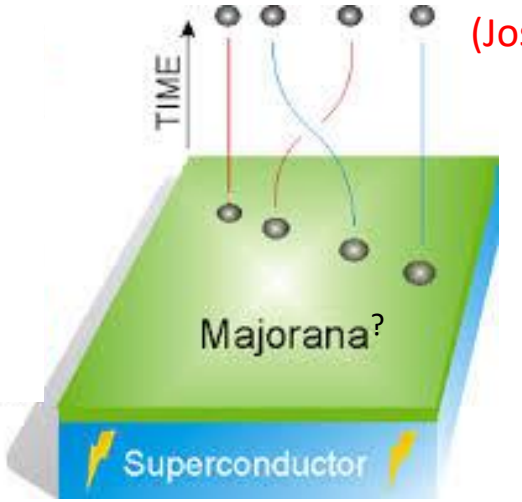
→topological quantum computing

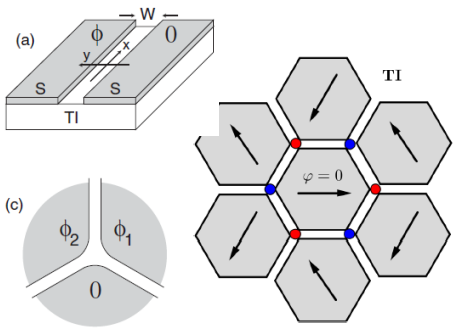




Build material/device platform for Fusing & Braining Majorana

(Josephson junction arrays on TI)





(mainly due to material-related defects/disorder…)

- **2D materials to reduce decoherence/noise in qubits/q-sensors**

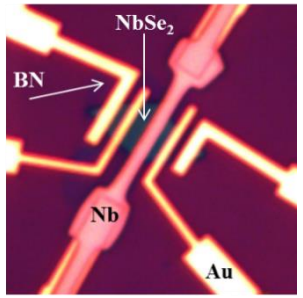
e.g. h-BN as dielectric tunnel barrier in Josephson Junctions

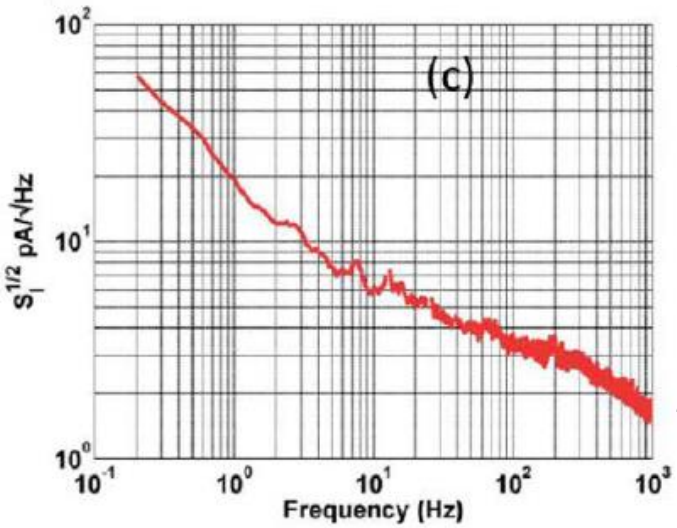
– better qubits & SQUIDs

h-BN dielectric promises better Josephson junctions (?!):

- 2D atomic crystal – near perfect lattice and crystallinity
- Ultralow defects -- (shown to be "best" dielectric)
- Clean interface with other 2D material superconductors

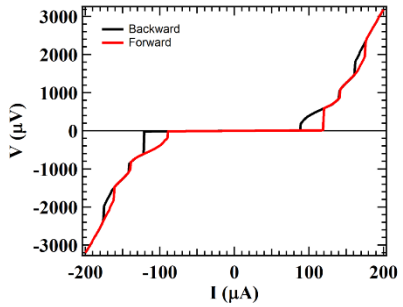
→ **Better qubit (lower decoherence) & sensor (lower noise)**





Already at least 4X lower noise than traditional Junctions!

(prelim.data, with R.McDermott)



APPLIED PHYSICS LETTERS **107**, 113101 (2015)

Observation of reduced 1/f noise in graphene field effect transistors on boron nitride substrates

Morteza Kayyalha[1,2] and Yong P. Chen[1,2,3,a)]
[1]Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA
[2]School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA
[3]Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA

Other possibilities: Graphene-passivated superconductor or 2D superconductor (eg. FeSe) might provide cleaner Superconductors in Josephson junctions?;

Graphene(passivated)-electrodes for low-noise ion trap electrodes?

Potential Project: 2D material (h-BN) based Josephson Junctions:

h-BN as dielectric tunnel barrier – *better qubits & SQUIDs*

Potential Sandia Collaborators: R.Lewis,

Josephson junctions: basis of SQUID and SC-qubits (another leading candidate for quantum computing)

*-- yet also hard to scale up due to **decoherence**)*

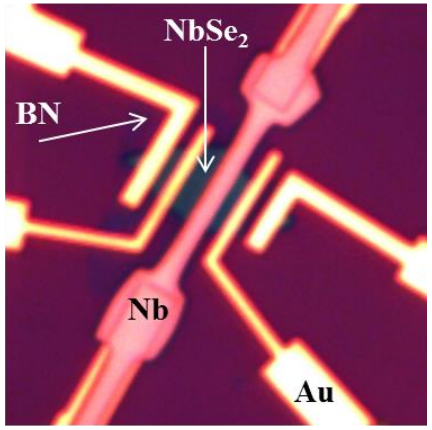
PRL 95, 210503 (2005) PHYSICAL REVIEW LETTERS week ending 18 NOVEMBER 2005

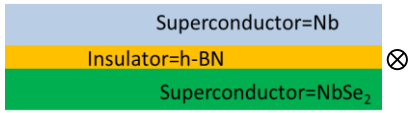
Again due to material defects/disorder in tunnel barrier & superconductor

Conventional J-junctions: (eg. Al/AlO$_x$/Al)
Metal-based superconductors (eg Al or Nb)
Oxide as dielectric tunnel barrier (eg. AlO$_x$)

Decoherence in Josephson Qubits from Dielectric Loss

John M. Martinis,[1,*] K. B. Cooper,[1] R. McDermott,[1] Matthias Steffen,[1] Markus Ansmann,[1] K. D. Osborn,[2] K. Cicak,[2] Seongshik Oh,[2] D. P. Pappas,[2] R. W. Simmonds,[2] and Clare C. Yu[3]





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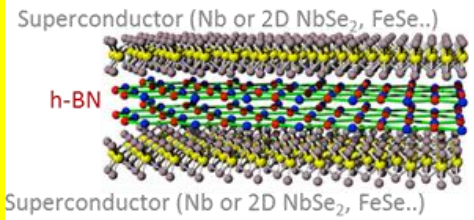
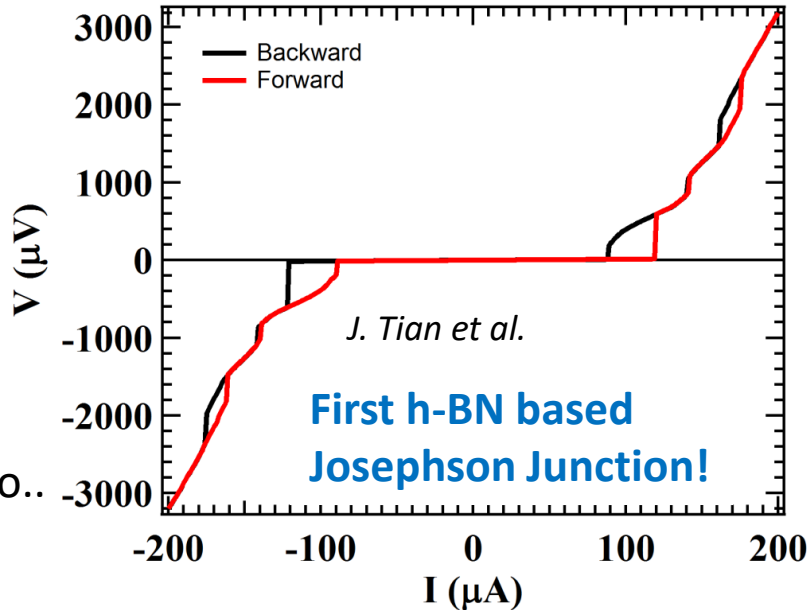
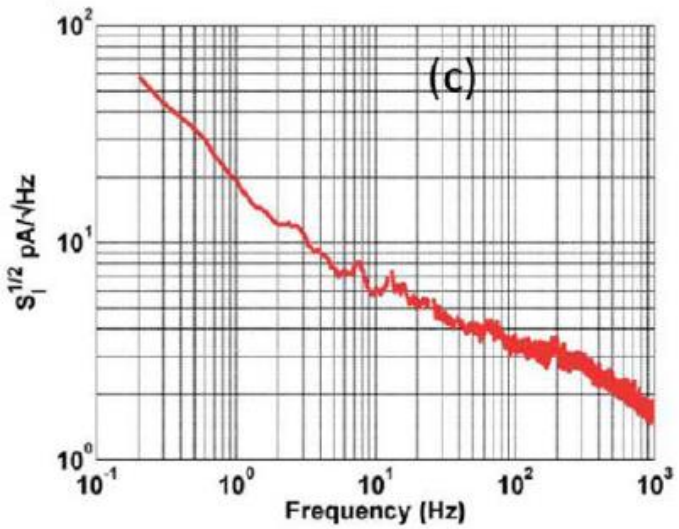
- Clean interface with other 2D material superconductors

→ **Better qubit (lower decoherence) & sensor (lower noise)**





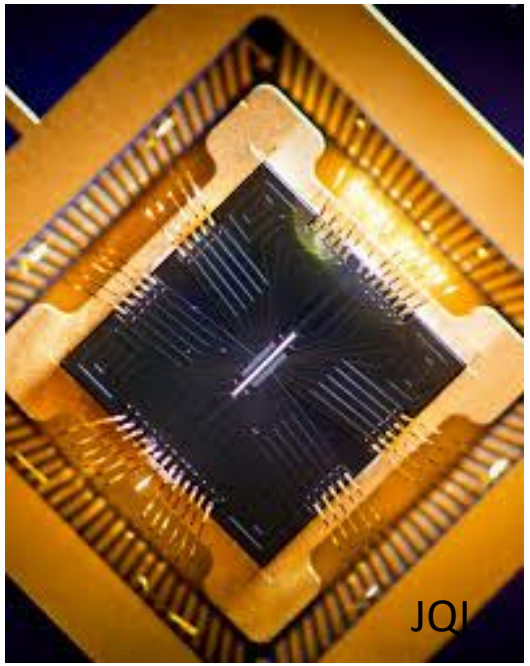


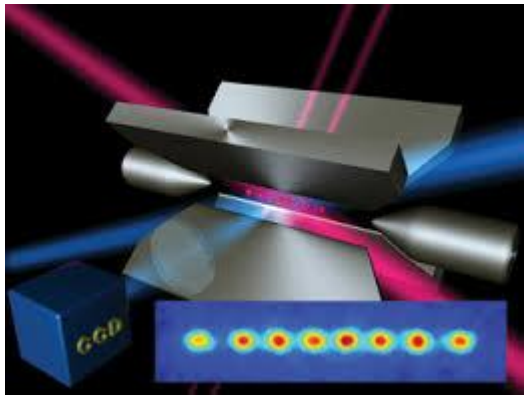
Already at least 4X lower noise than traditional Junctions!

Graphene-passivated superconductor or 2D superconductor (eg. FeSe) can provide cleaner superconductor too..

Potential Project 2: Graphene-based electrodes for ion traps

Potential Sandia Collaborators: D.Stick,



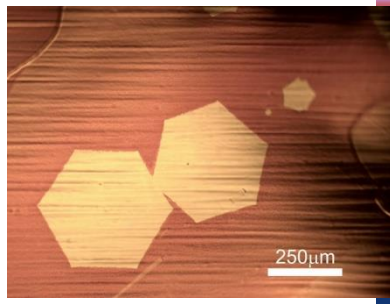


Trapped ions: one of the two leading candidates for quantum computing

Still limited to small number (~10) qubits due to decoherence

Decoherence mainly due to noise (current/field fluctuation) in electrodes (Au) [grains; defects; adsorbates etc..]

Graphene has shown promise to be a new low-noise, 'clean' surface conductor free from such issues (single crystalline, inert surface etc.)

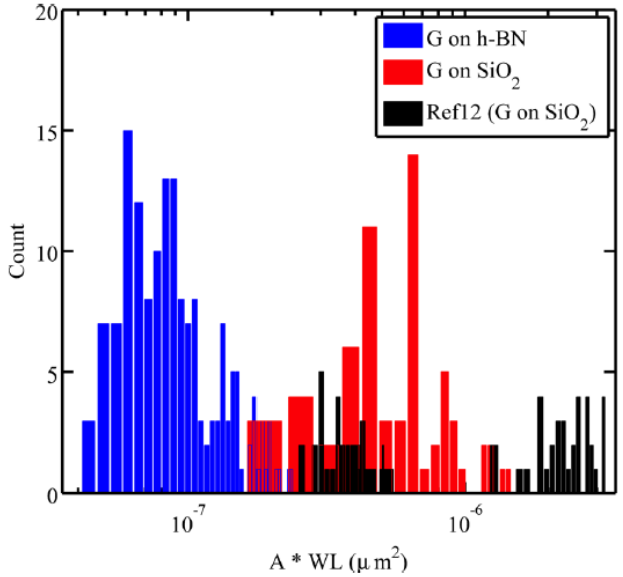


CVD single crystal graphene (Chen)

APPLIED PHYSICS LETTERS **107**, 113101 (2015)

Observation of reduced 1/f noise in graphene field effect transistors on boron nitride substrates

Morteza Kayyalha[1,2] and Yong P. Chen[1,2,3,a)]
[1]*Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA*
[2]*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA*
[3]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*



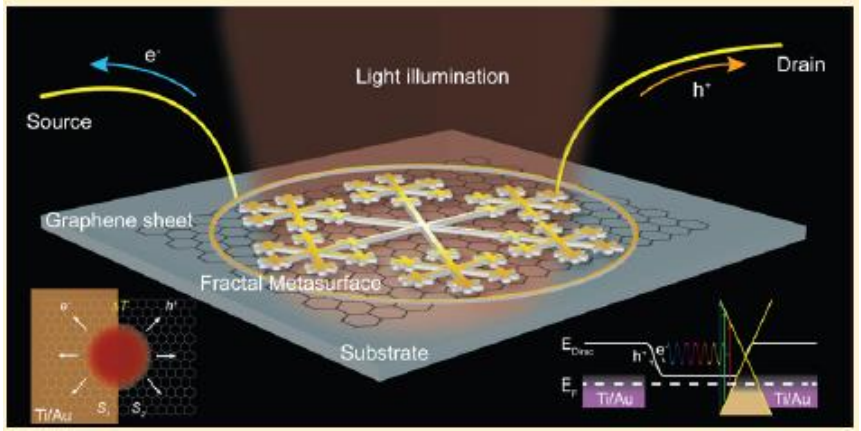
NANO LETTERS
Letter
pubs.acs.org/NanoLett

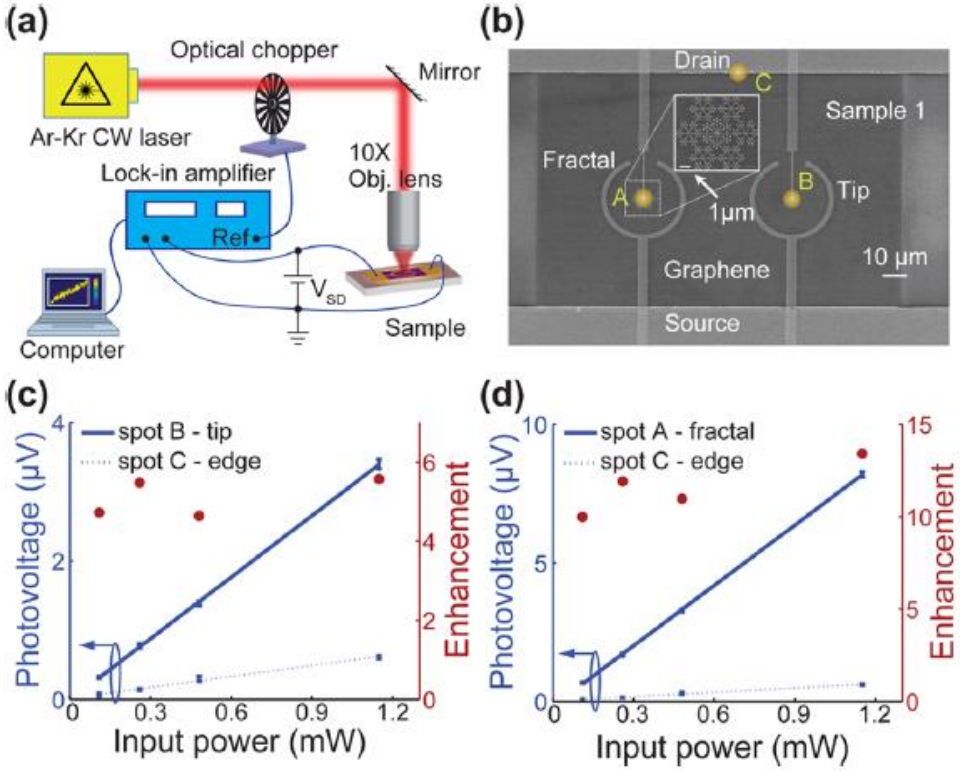
Enhanced Graphene Photodetector with Fractal Metasurface

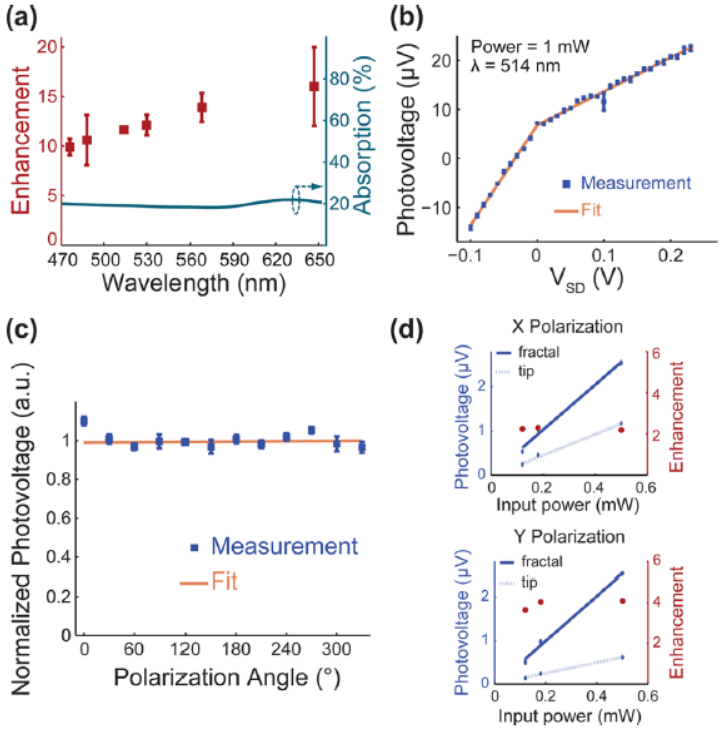
Jieran Fang,[†,§] Di Wang,[†,§] Clayton T. DeVault,[‡,§] Ting-Fung Chung,[‡,§] Yong P. Chen,[†,‡,§] Alexandra Boltasseva,[†,§,∥] Vladimir M. Shalaev,[*,†,§] and Alexander V. Kildishev[*,†,§]

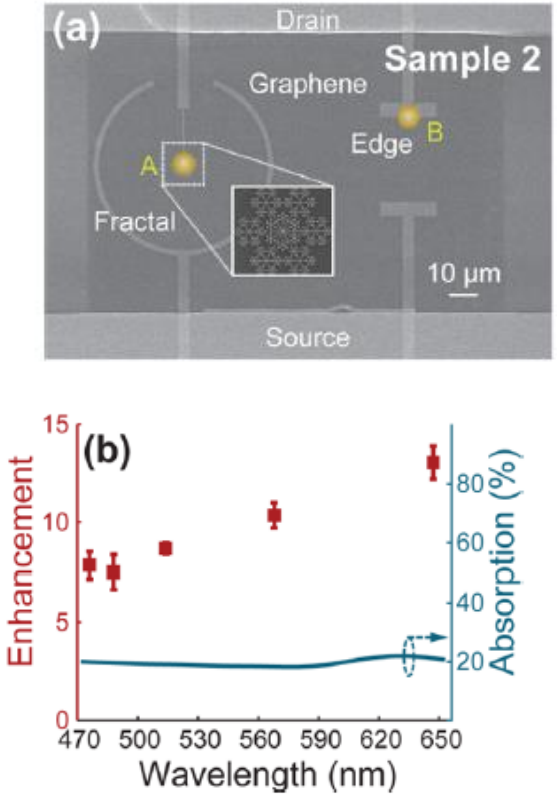
[†]School of Electrical and Computer Engineering, [‡]Department of Physics and Astronomy, and [§]Birck Nanotechnology Center and Purdue Quantum Center, Purdue University, West Lafayette, Indiana 47907, United States

[∥]DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Lyngby, DK-2800, Denmark





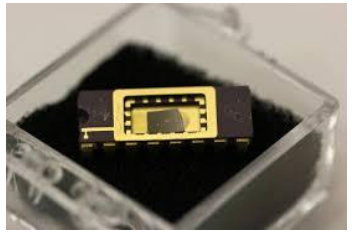


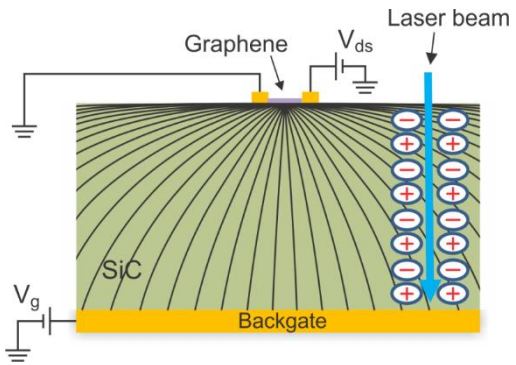


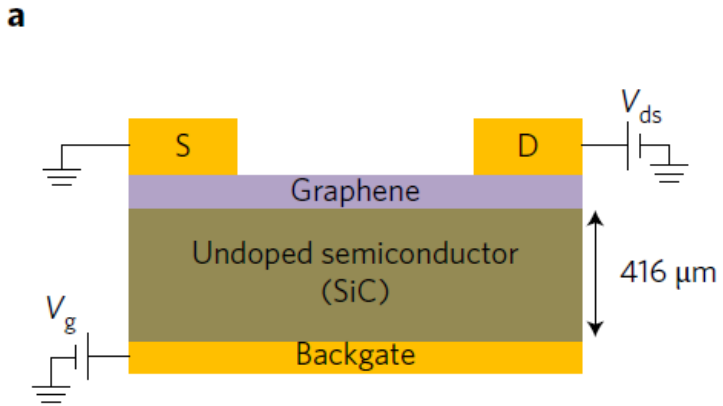
Research Spotlight Forum

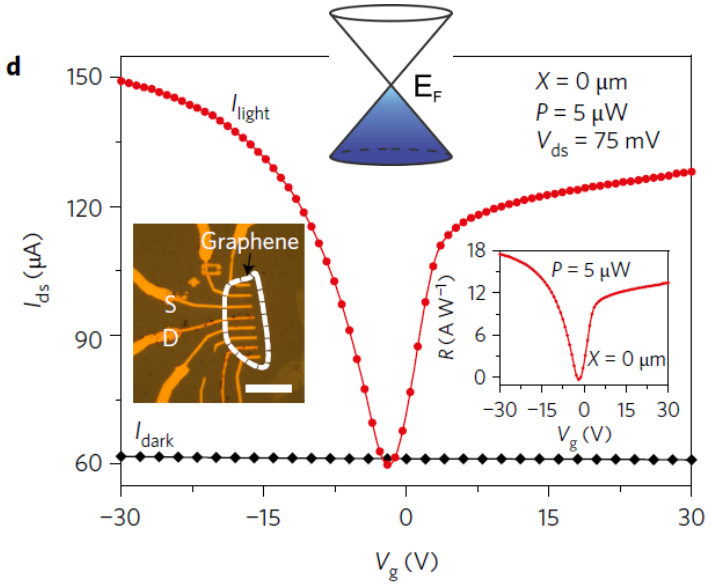
Graphene on SiC as photo-actuated FET ("phototransistor") → *large-area, nonlocal* photodetection/imaging (by few pixels)

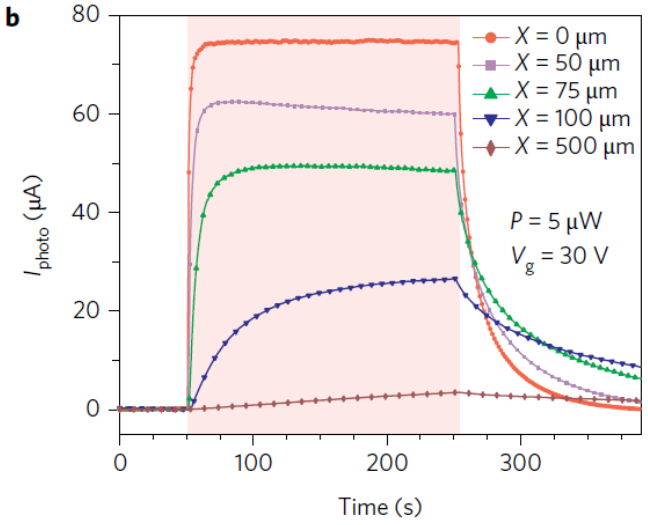
Biddut Sarker et al. [YPC] **Nature Nanotech.** 12, 668-674 (2017)

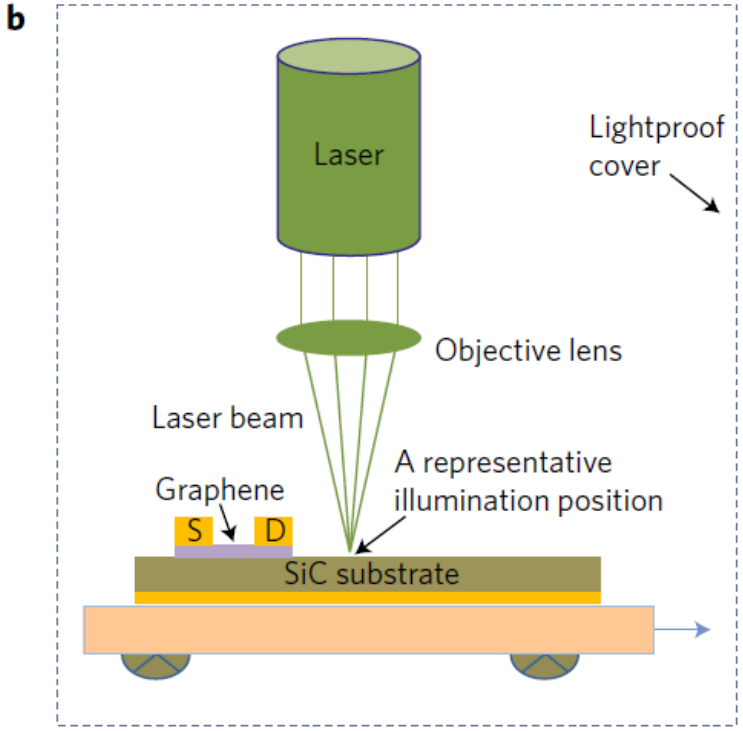


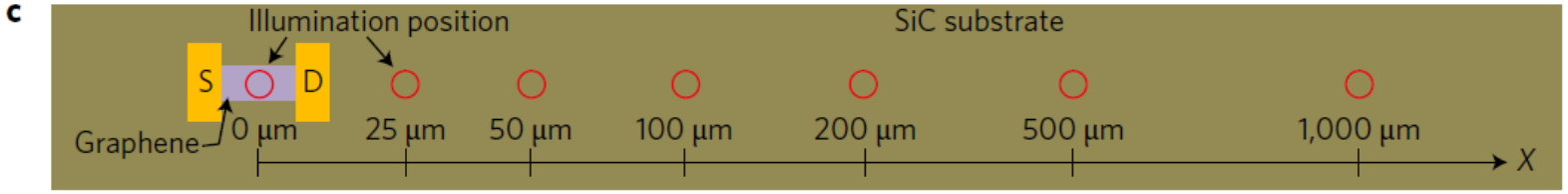












APPLIED PHYSICS LETTERS **106**, 223503 (2015)

Position sensitivity of graphene field effect transistors to X-rays

Edward Cazalas,[1,a),b)] Biddut K. Sarker,[2,3,b)] Michael E. Moore,[1] Isaac Childres,[2,3] Yong P. Chen,[2,3,4] and Igor Jovanovic[1]

[1]*Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
[2]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
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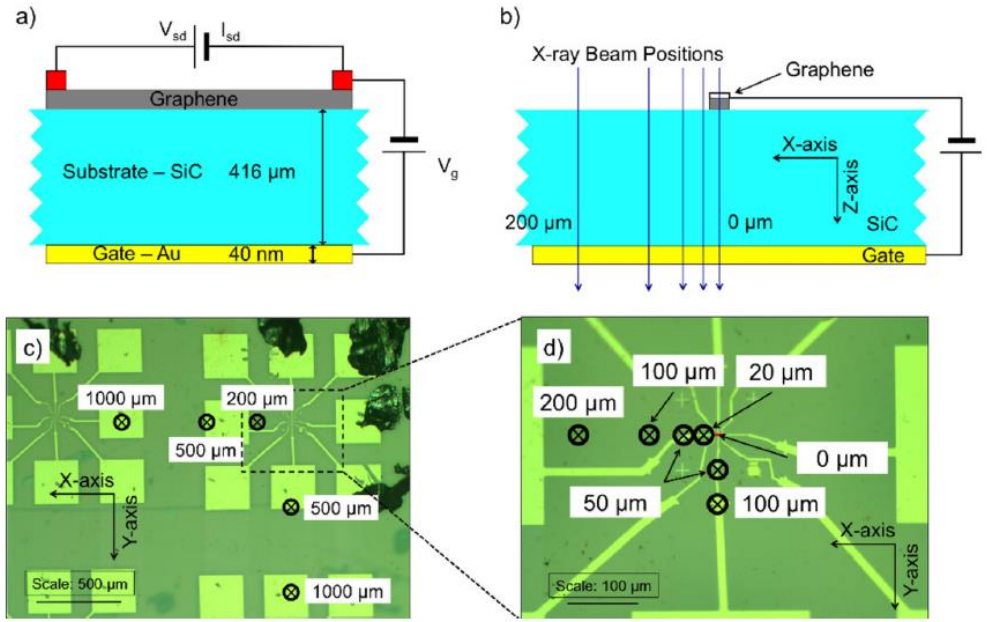
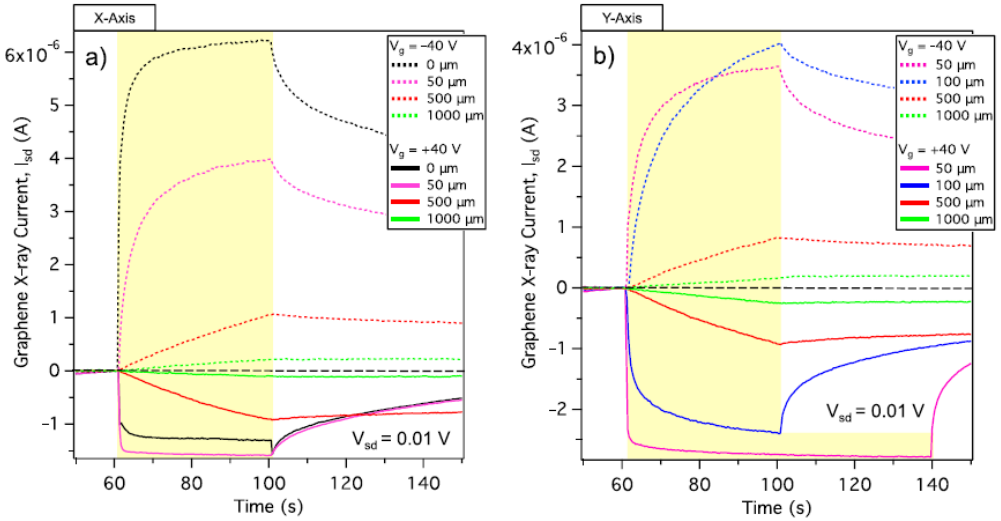
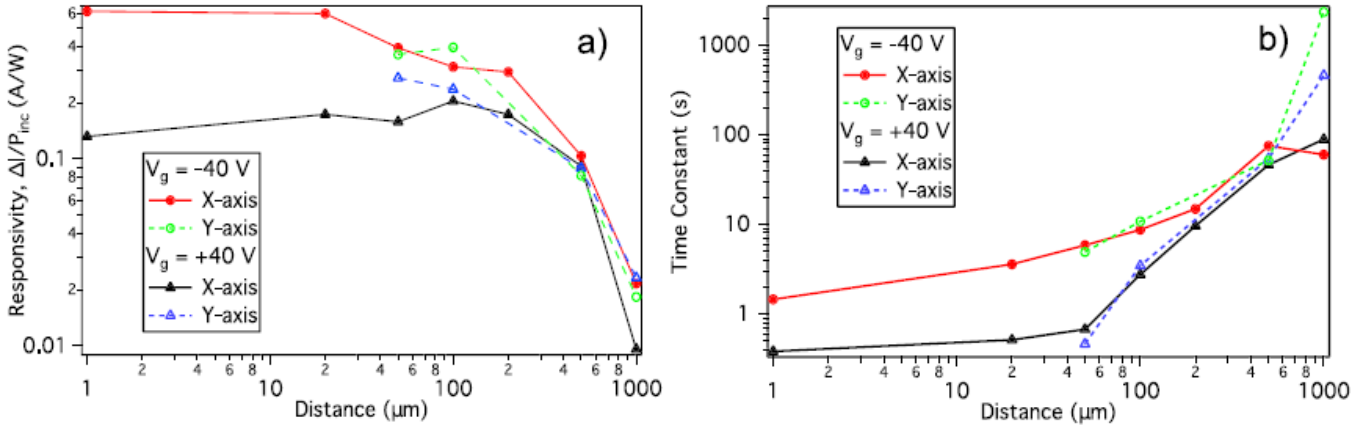
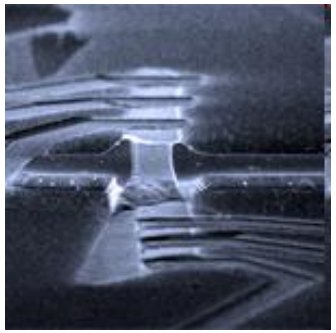




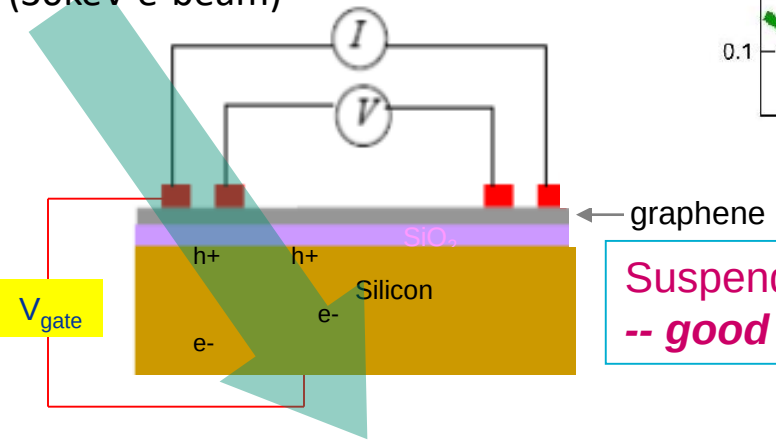


Radiation Response and **Radiation hardness** of graphene trans

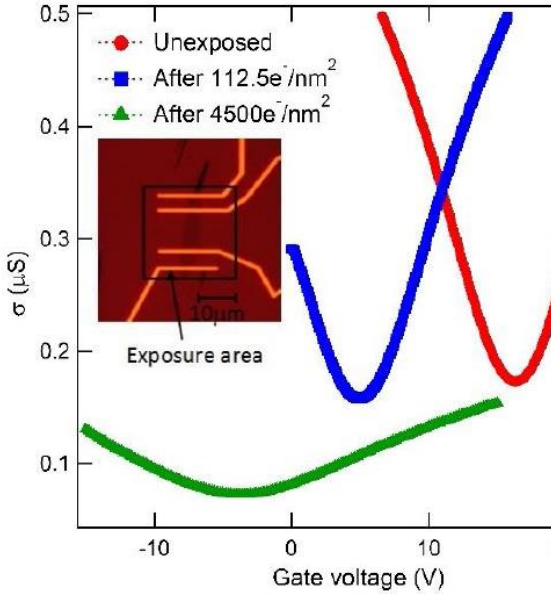
(graphene FET on SiC)



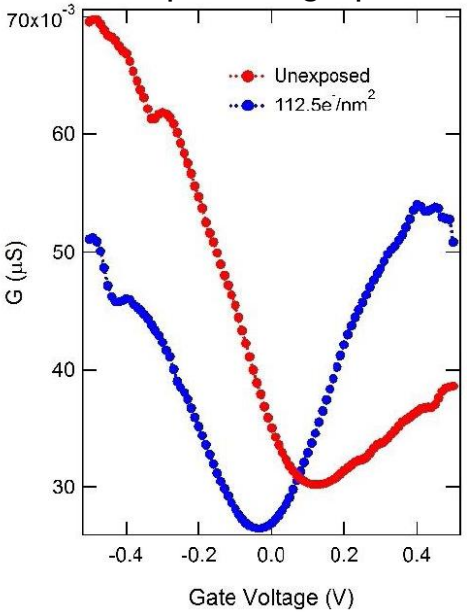
(30keV e-beam)

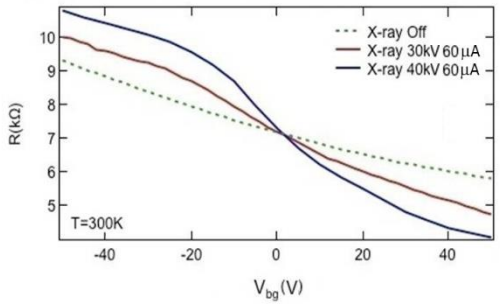


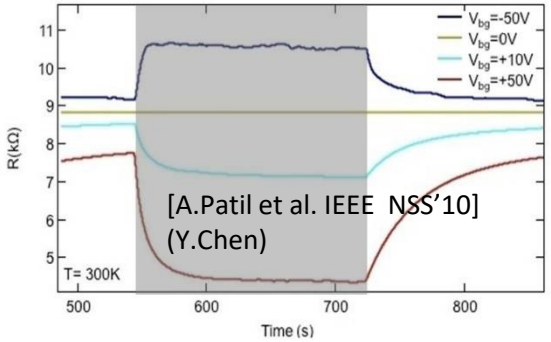
Supported on SiO_2/Si



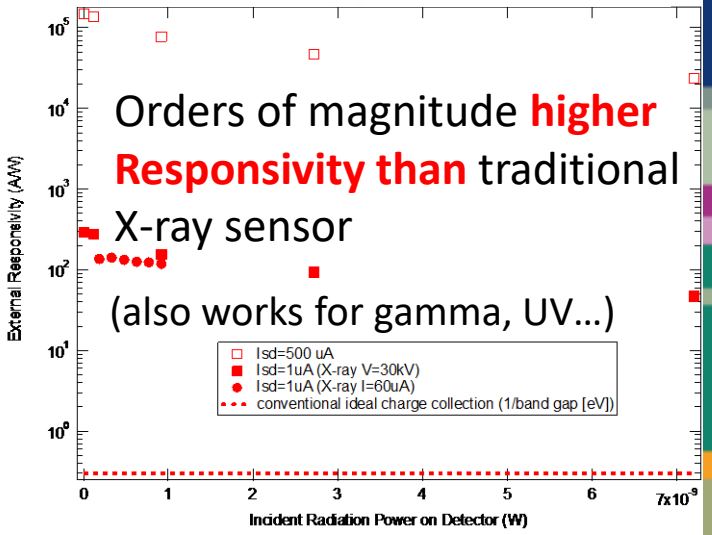
Suspended graphene







[A.Patil et al. IEEE NSS'10]
(Y.Chen)



Orders of magnitude **higher Responsivity than** traditional X-ray sensor

(also works for gamma, UV…)

Suspended graphene (no substrate): much smaller shift!
-- good for rad-hard electronics?!

I.Childres et al. Appl. Phys. Lett. (2010) [Y.Chen]
I. Childress et al. SPIE proceeding (2011)

-High energy electrons ionize e-h pairs in Si wafer
-Less mobile holes trapped at oxide-Si interface, inducing electrons in the channel (graphene)
-Analogous to the well-known negative-shift of threshold voltage in MOSFET subject to high energy ionizing irradiation

RESEARCH NEEDS

Describe any gaps or new directions that would benefit from collaboration.

- Access to QIS hardware platforms/"testbeds"techniques: trapped ions, Josephson junction QC, single atoms.. etc.
- Measurement/metrology/testing tools: scanning probe, elemental analysis,
- Processing tools: ion implantation, radiation/beam sources …
- Computational: first principle (DFT+) materials simulation (bands, defects, …)