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14. ABSTRACT slides from Aug 2014 all hands conf call
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15. SUBJECT TERMS powerpoint slides
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Report Title

Slides from Aug 2014 all hands conf call

ABSTRACT

slides from Aug 2014 all hands conf call

**MURI all-hands conference call Agenda
8/7/2014**

1. Annual Progress Report (Peter/Brittany)
 - a. Technical Report (1 page each)
 - b. Data Spreadsheets
 - c. File Management / Dropbox
2. Invoice Processing (Brittany)
3. Thrust Area Reports
 - a. Yale (Test Bed I)
 - b. UCI (Test Bed II, Func Sch II)
 - c. Penn (Test Bed III)
 - d. Seeman (Func Sch I)
 - e. Stroschio (Func Sch I)
 - f. Marshall (Func Sch I)
 - g. Brown (THz characterization)
4. Other Research Reports

Yale: Fabrication of SiNW Testbed

Progress: Attachment Structures for DNA Origami
Assembly

9 chips delivered

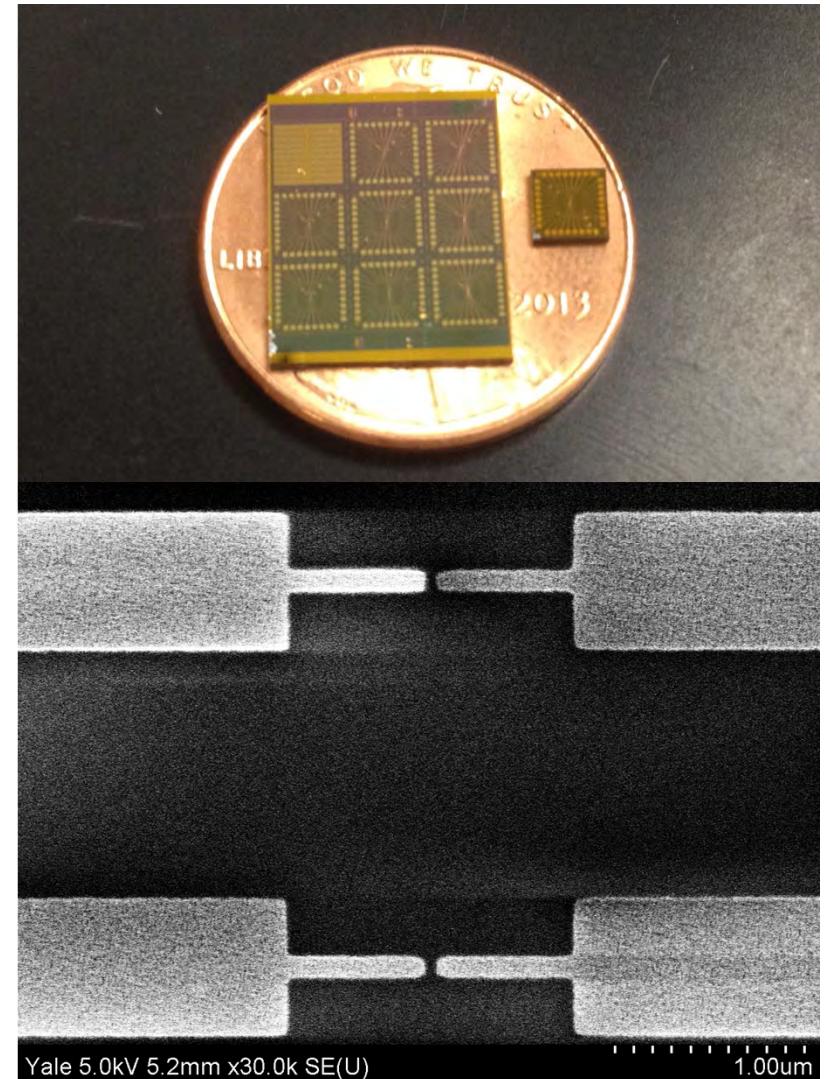
Design

Goal

Fabricate device with electrode pairs to manipulate/measure DNA Origami structures.

Constraints

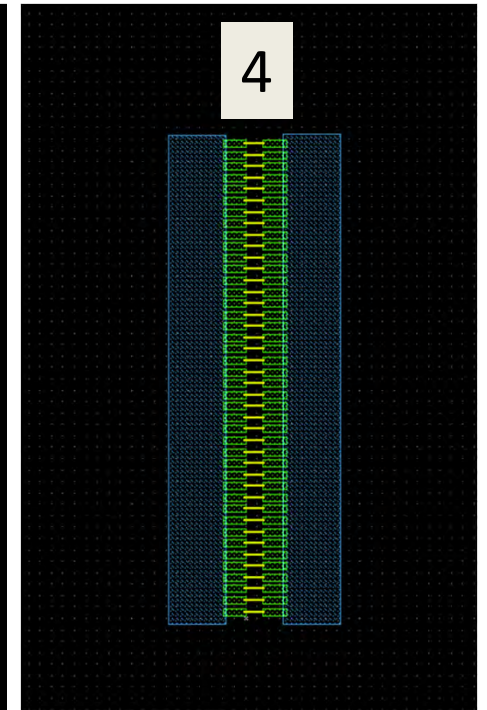
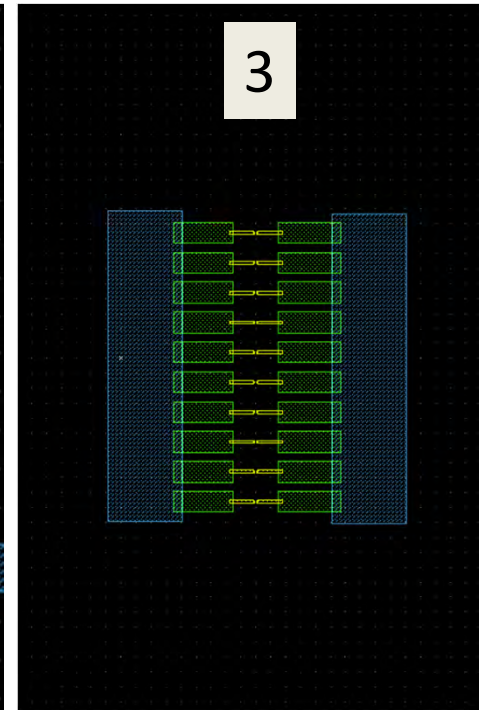
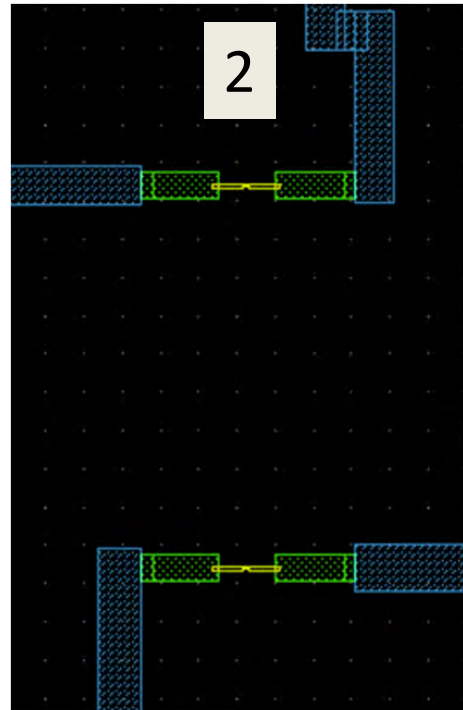
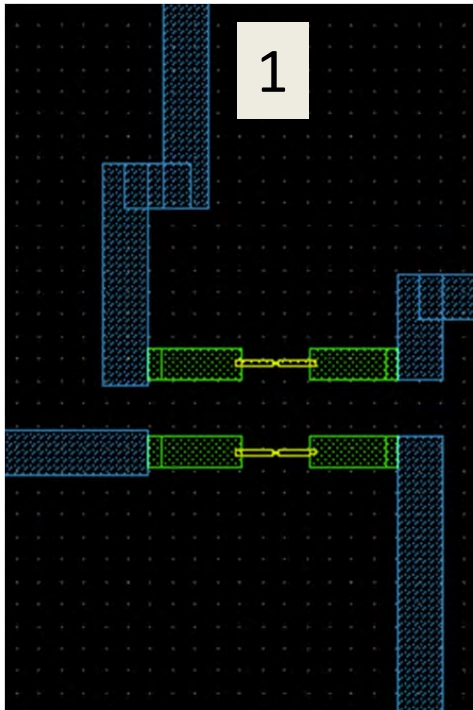
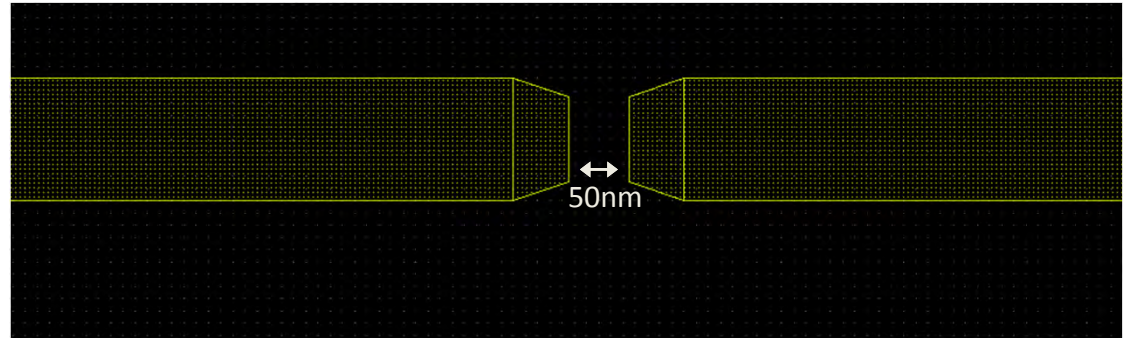
1. Metal thickness: Electrode pairs must be thin enough to not interfere with AFM of origami structures (7nm)
2. Geometry: gap between electrodes must be the size of an origami structure (50nm)
3. Interface: must be able to connect to chip and conduct all experiments under AFM, in solution, all with same scan direction



Design

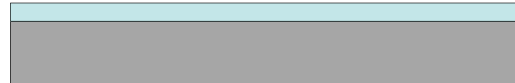
4 structure layouts:

1. Single contact sites, 2um pitch
2. Single contact sites, 10um pitch
3. Array of 10 contact sites, 1um pitch
4. Array of 42 contact sites, 1um pitch

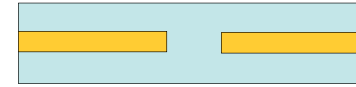


Fabrication

1. Wafer with oxide



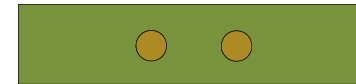
1. Optical lithography and metal deposition of leads



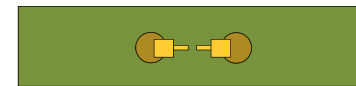
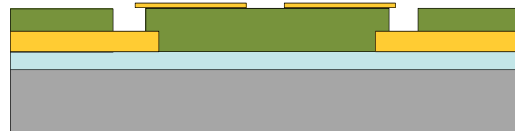
1. Deposit silicon nitride



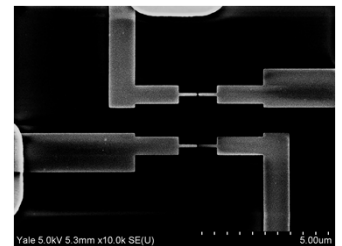
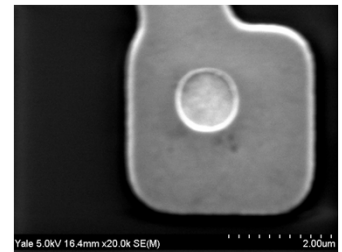
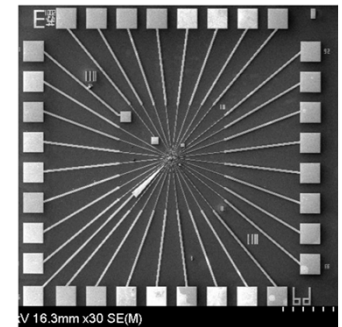
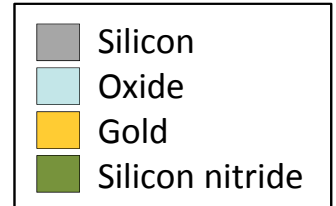
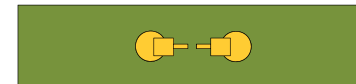
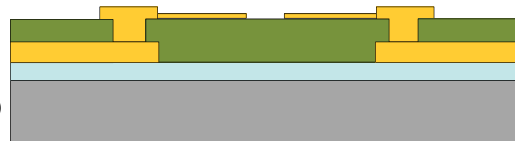
1. Open vias in nitride



1. E-beam lithography and thin metal deposition of electrode structures (2nm Cr + 5nm Au)

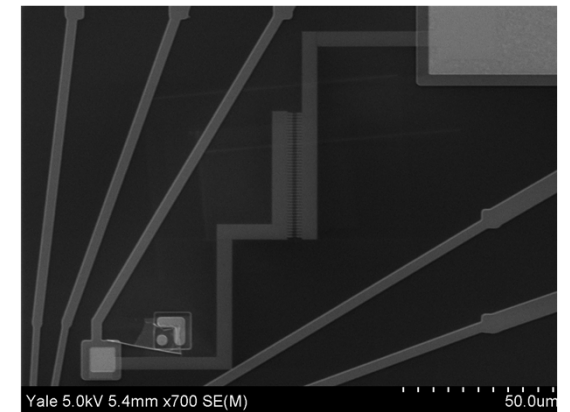
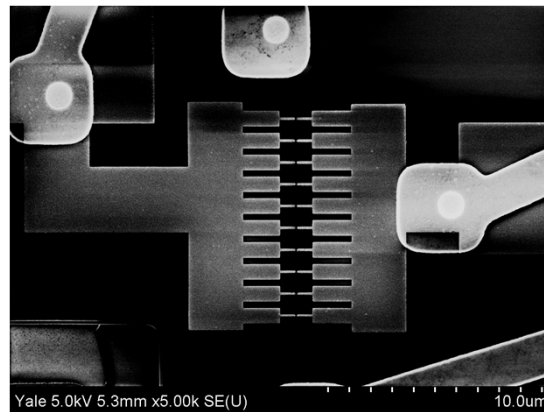
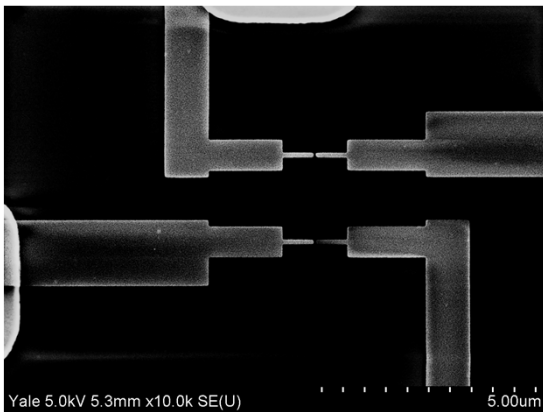
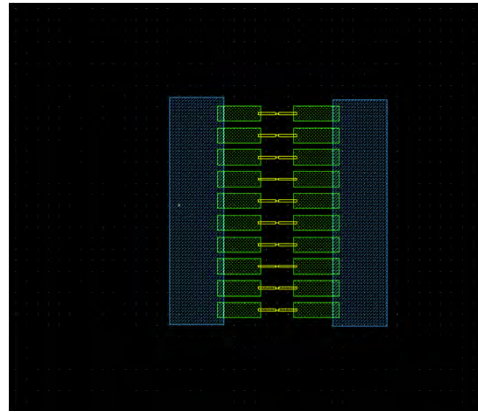
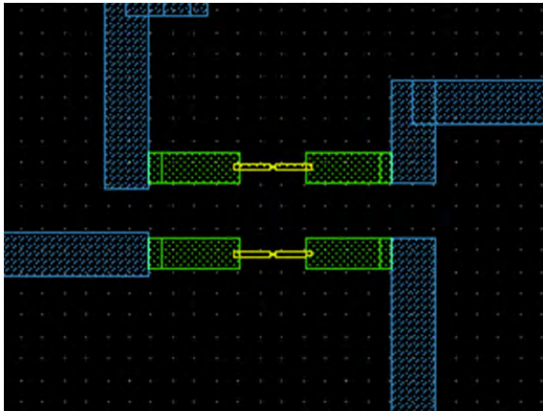


1. E-beam lithography and metal deposition to connect underlying leads to electrode structures



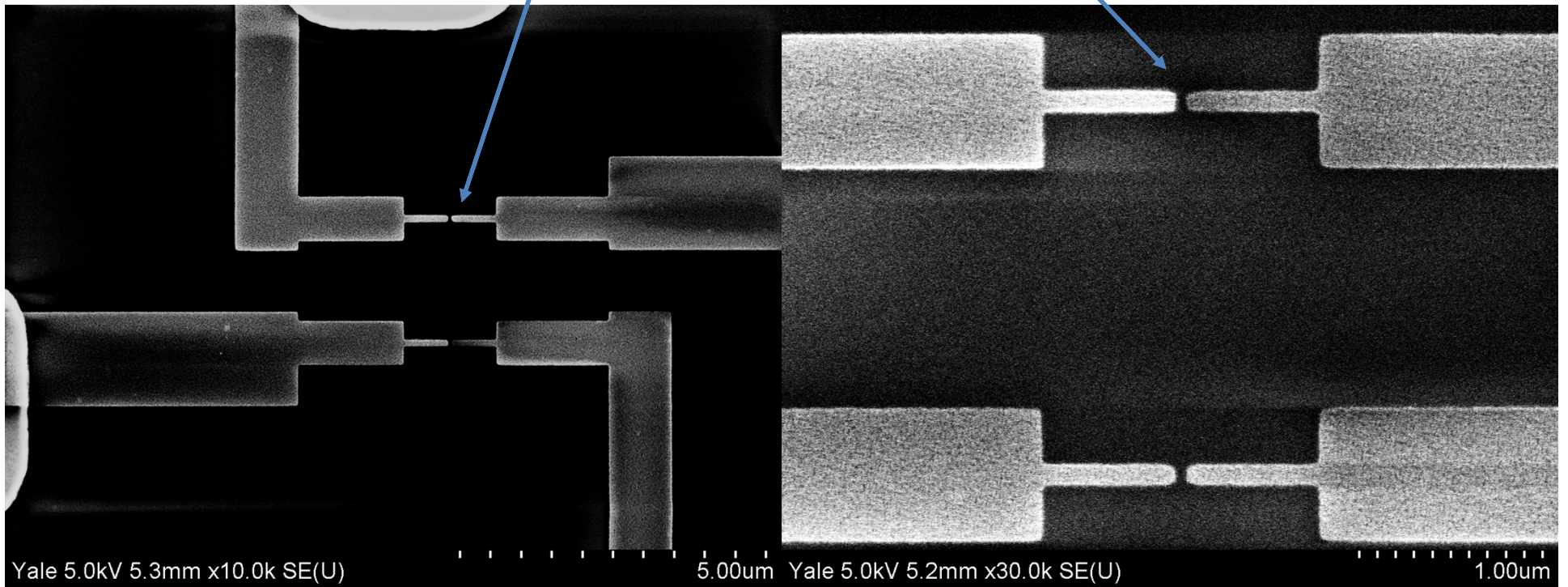
Fabrication

Structure realization



Fabrication

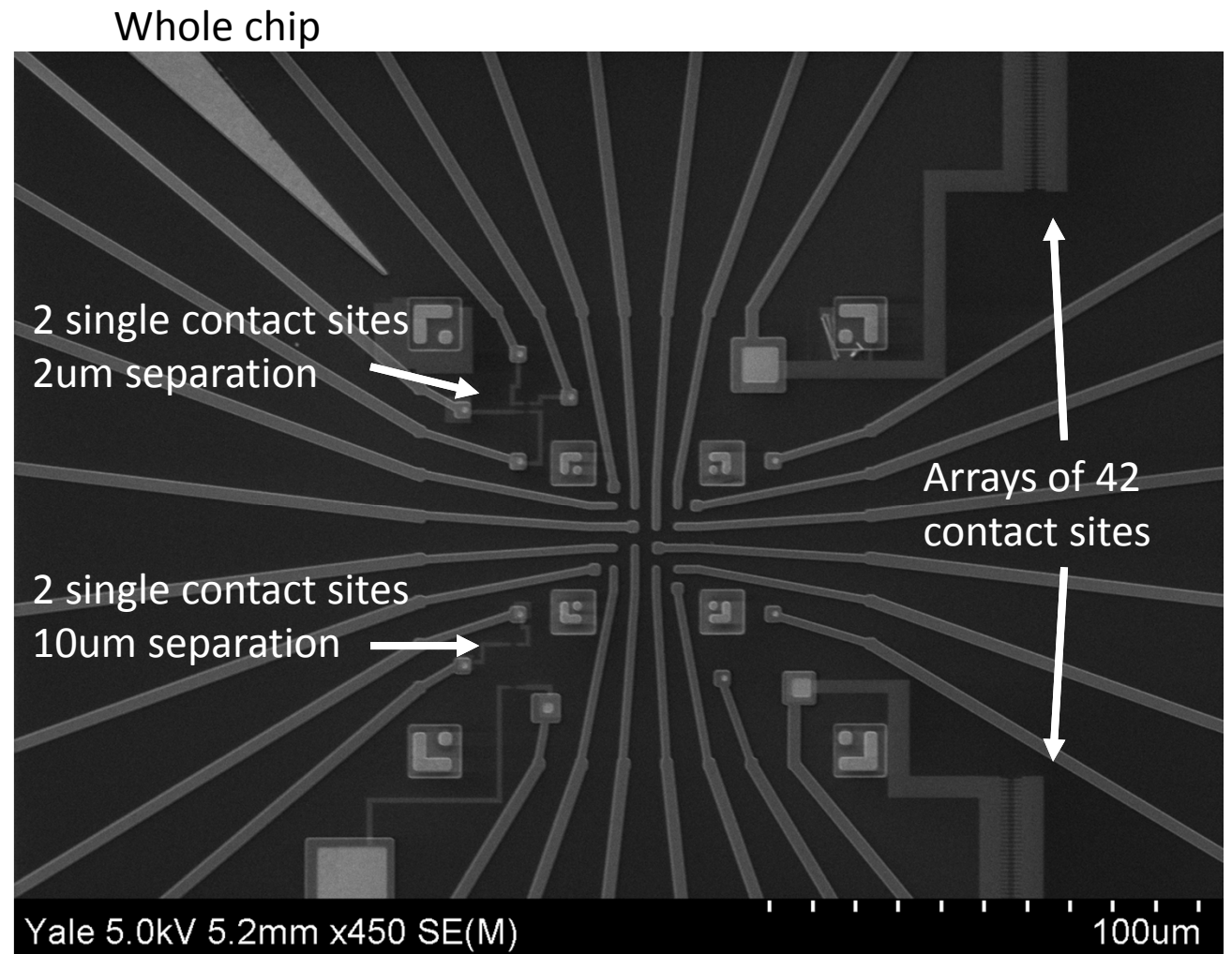
50nm gap between electrodes
for origami structures



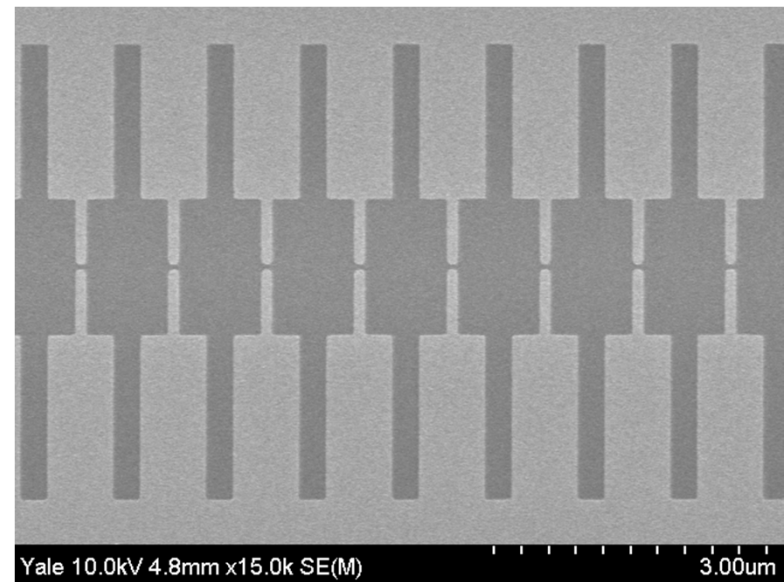
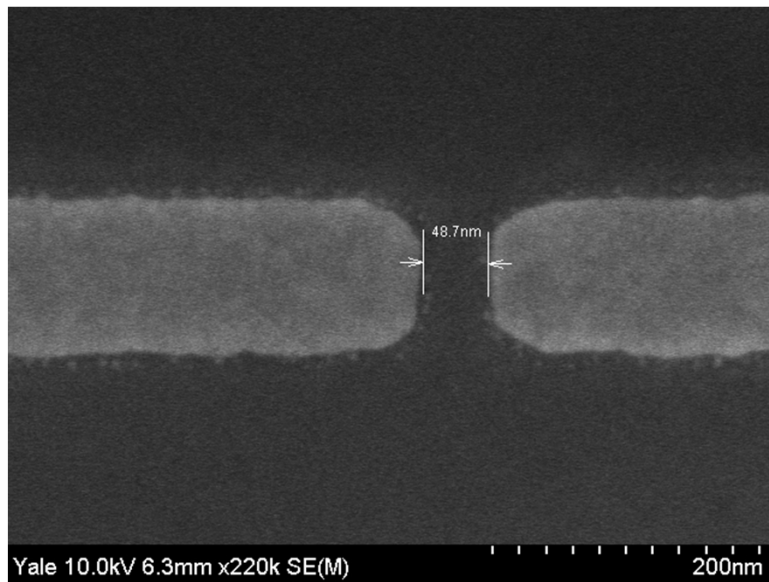
2 single contact sites w
independent leads

2 contact sites on a 42
contact site array

Fabrication

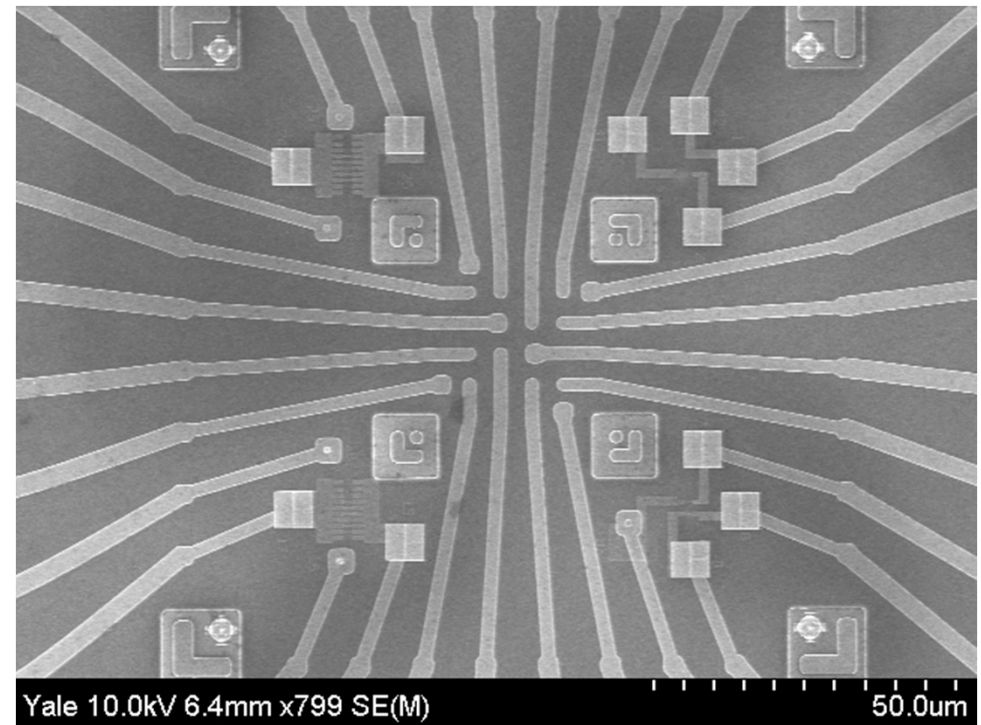


Fabrication – the good

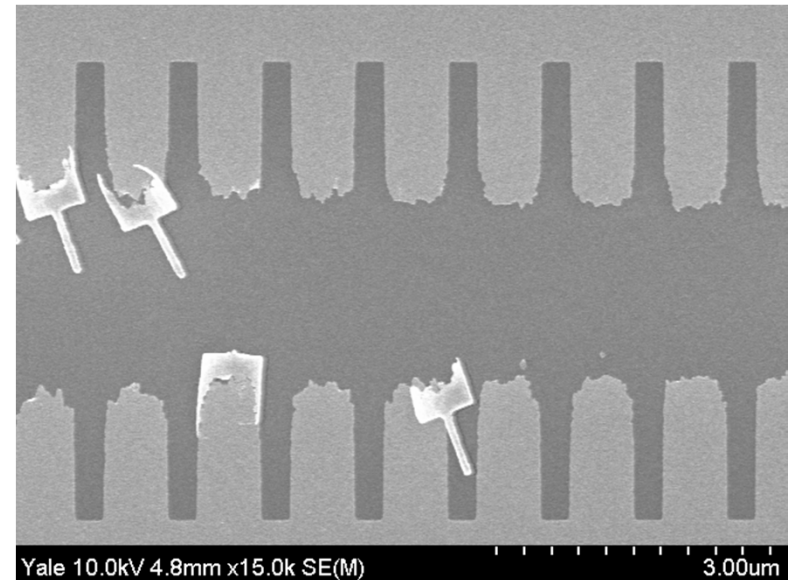
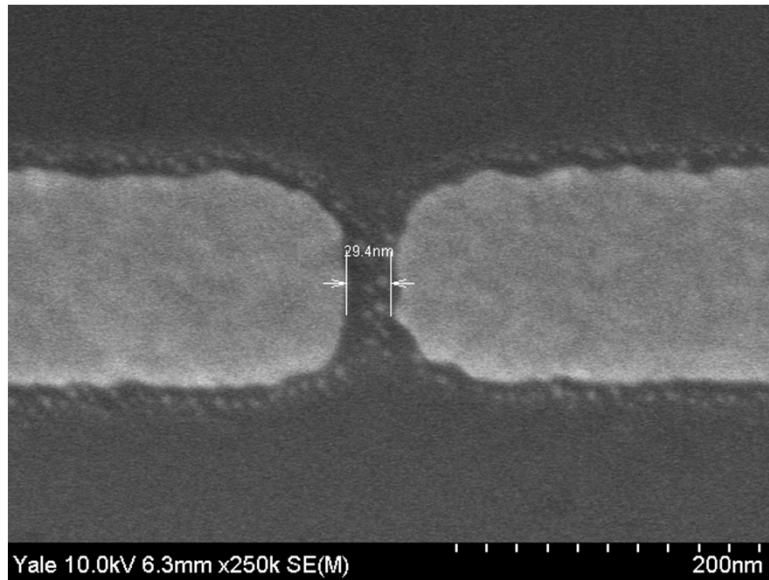


Achieved ~50nm gaps thin metal, with thick via metal

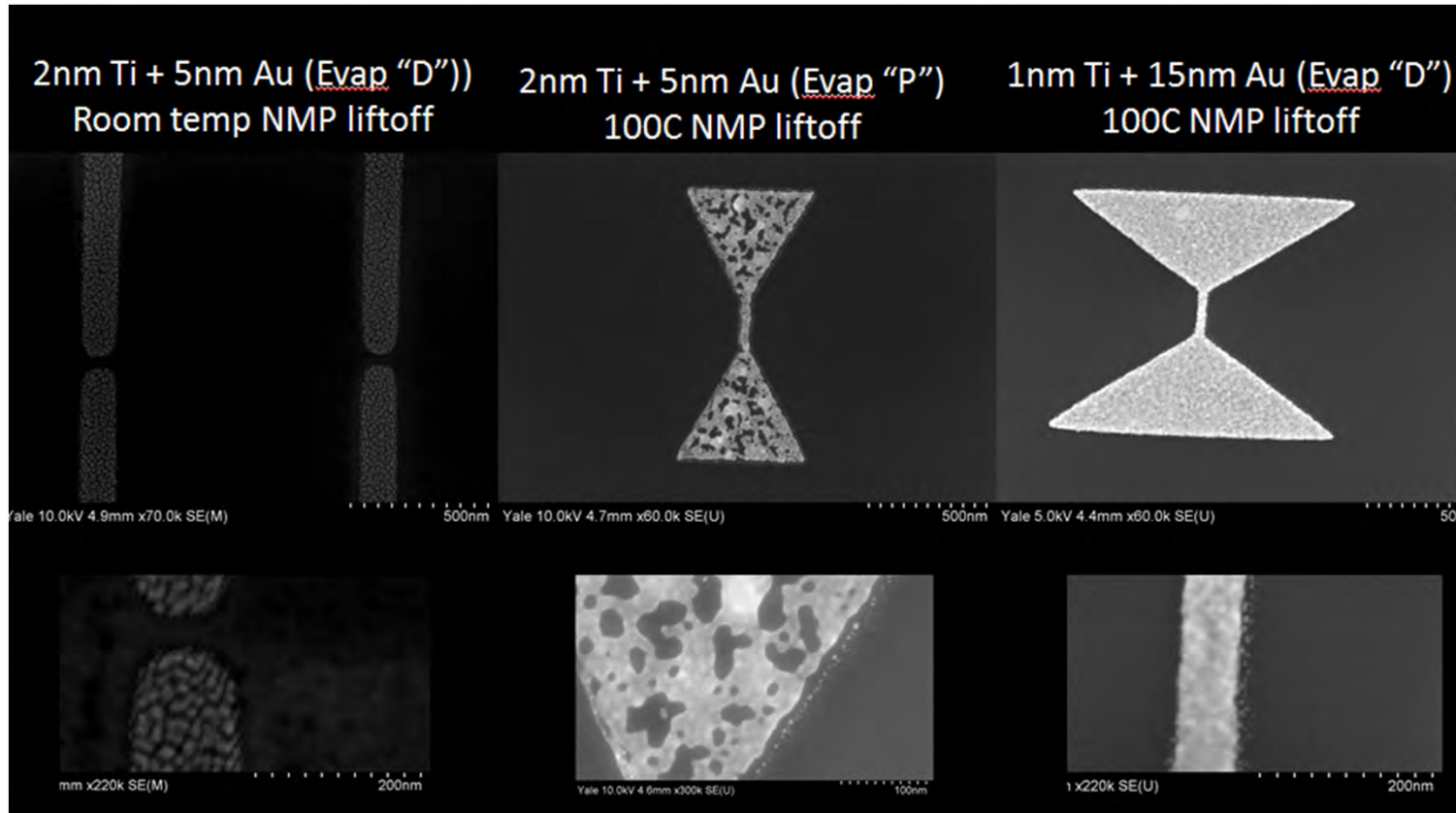
1. All alignment issues solved
2. Dosage for all structures (layer 1) determined
3. Dosage for all vias (layer 2) determined
4. Successful metal connection
5. Shadow mask for layer 3 has been Designed, fabricated, and received
6. Glass mounting slide design finalized, designed, received
7. Chip-to-slide process with smooth epoxy ramp has been done

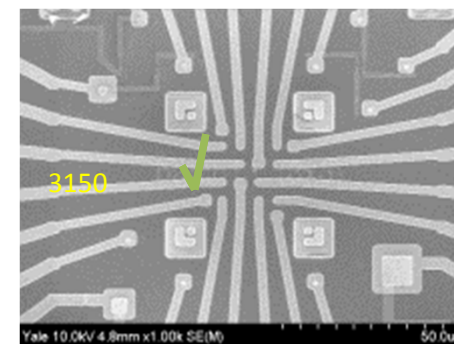
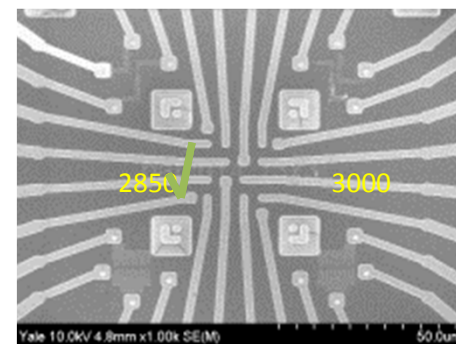
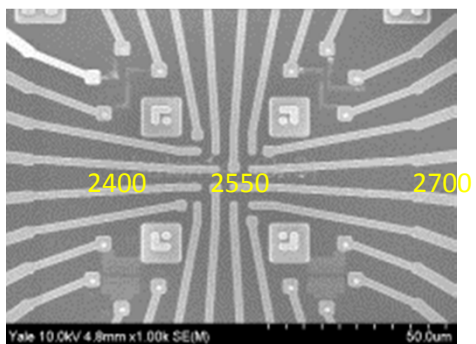
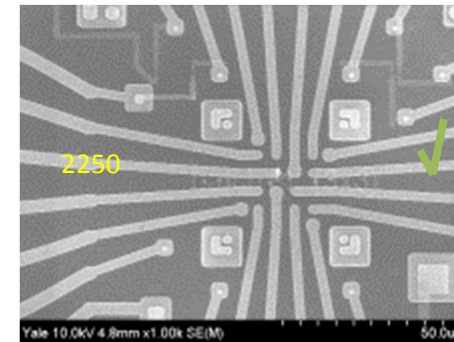
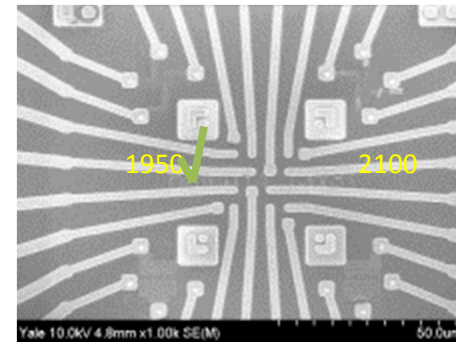
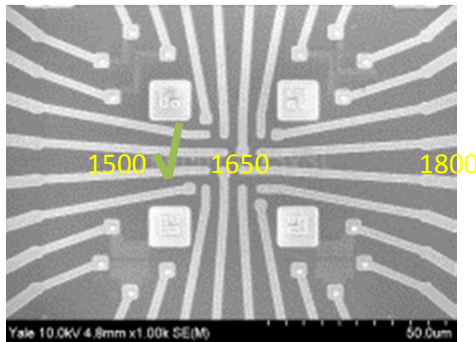
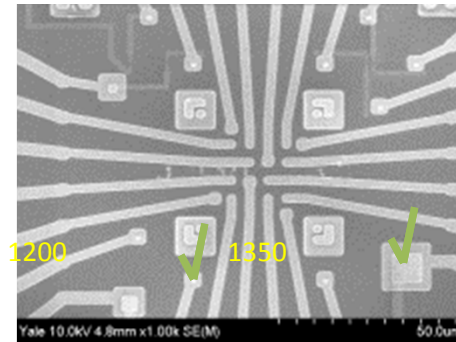
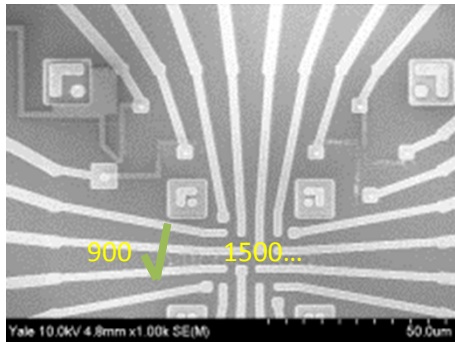


Fabrication – the bad



Fabrication – the ugly





Origami batch 14 (dose test) post thin metal

Need for proximity correction

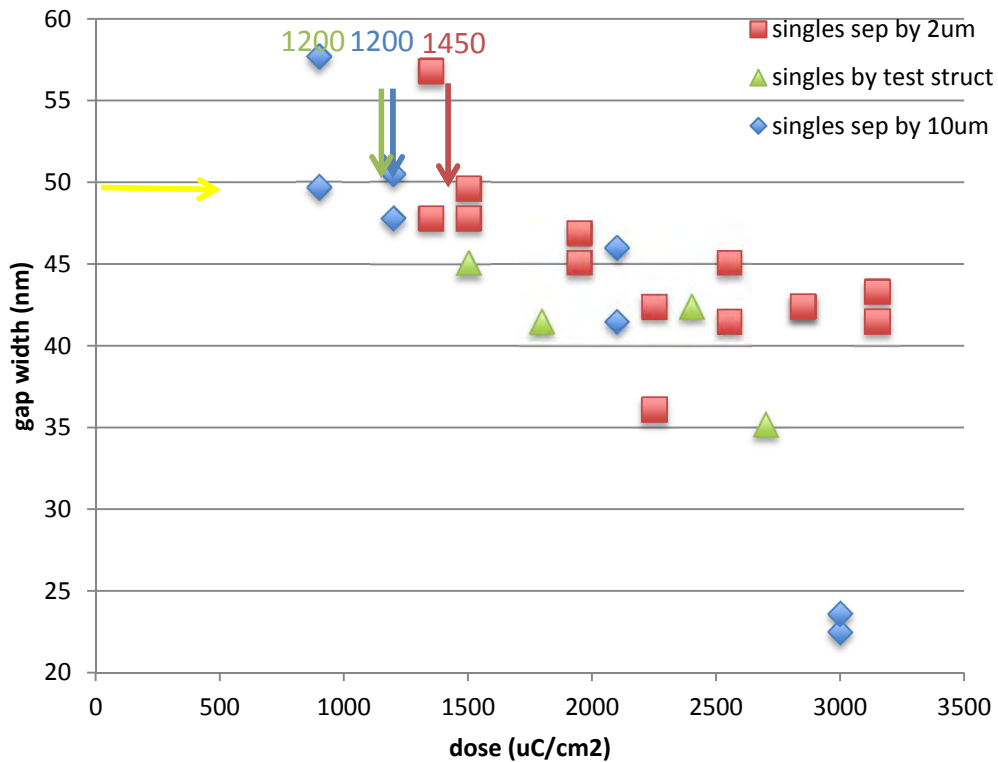
✓ = leads are good

Finger gap data for origami batch 14 dose test

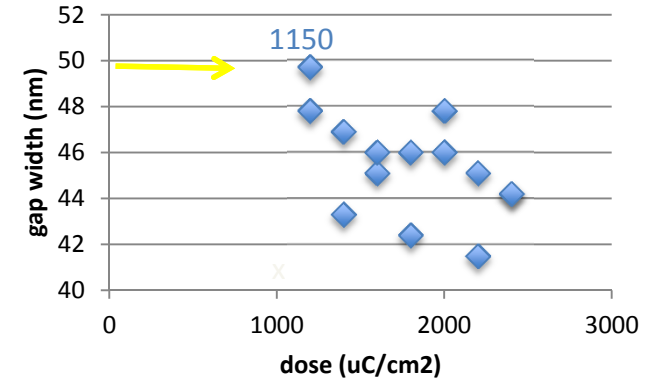
Desired gap = 50nm

Dose chosen to proceed

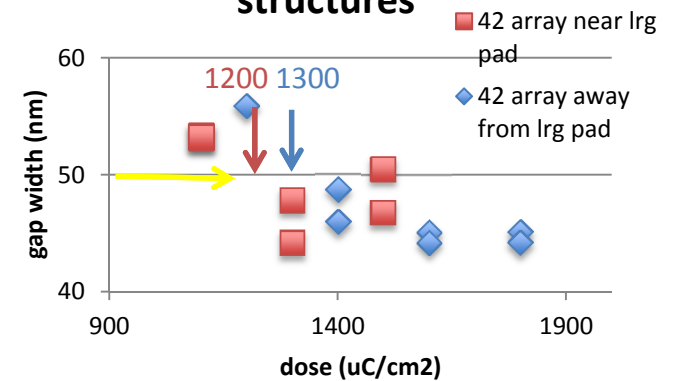
Gap width of single tip structures



Gap width of 10array structures

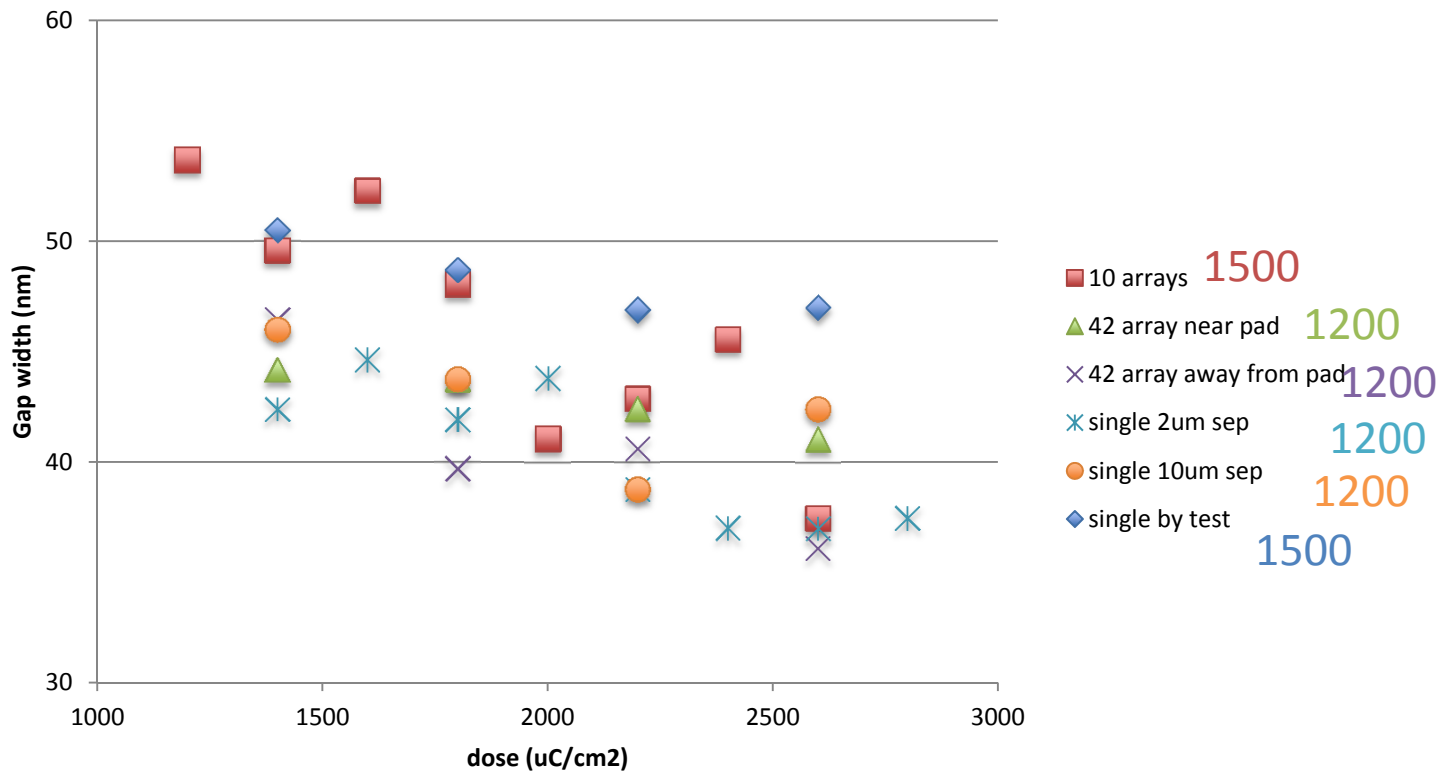


Gap width for 42 array structures



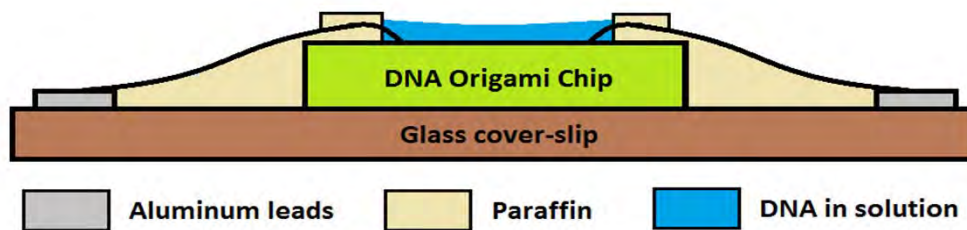
Org batch 16 dose test of thin metal layer (now that have leads without via covers.)

Gap width of origami structs

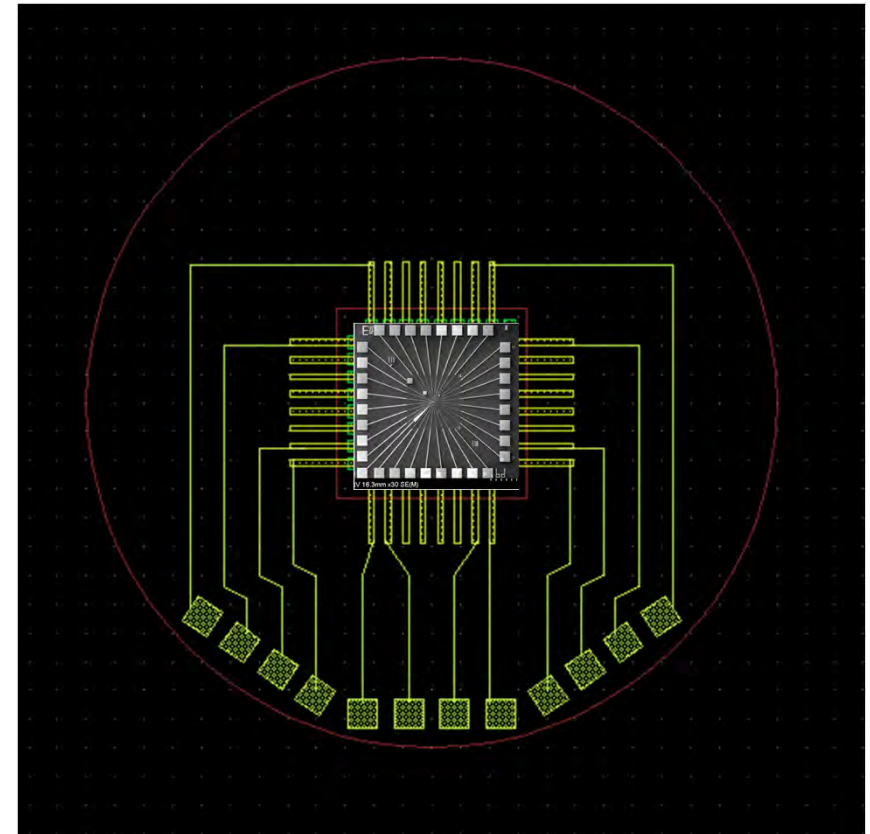


Interfacing

- Chip dimensions do not exceed 3.5mm x 3.5mm
- Chip mounted on glass cover-slip 12mm circle to fit in AFM
- Pads to all relevant electrodes on front, fabricated via shadow-mask deposition
- Paraffin supports aluminum leads and contains DNA in solution for active manipulation under AFM



Cross-section of target packaging



Top-view of target packaging

Yale: Fabrication of SiNW Testbed

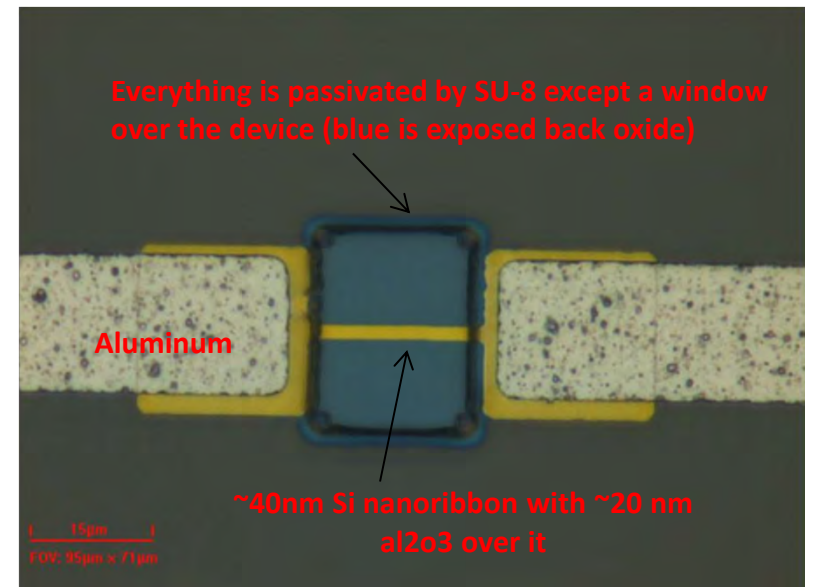
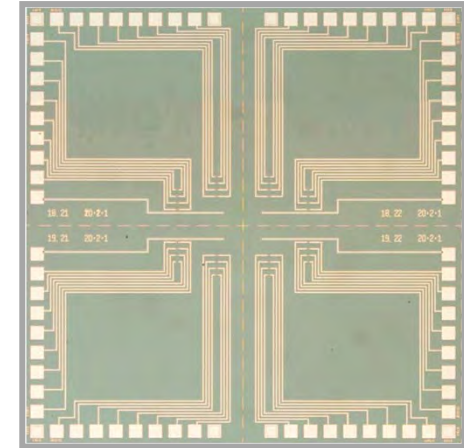
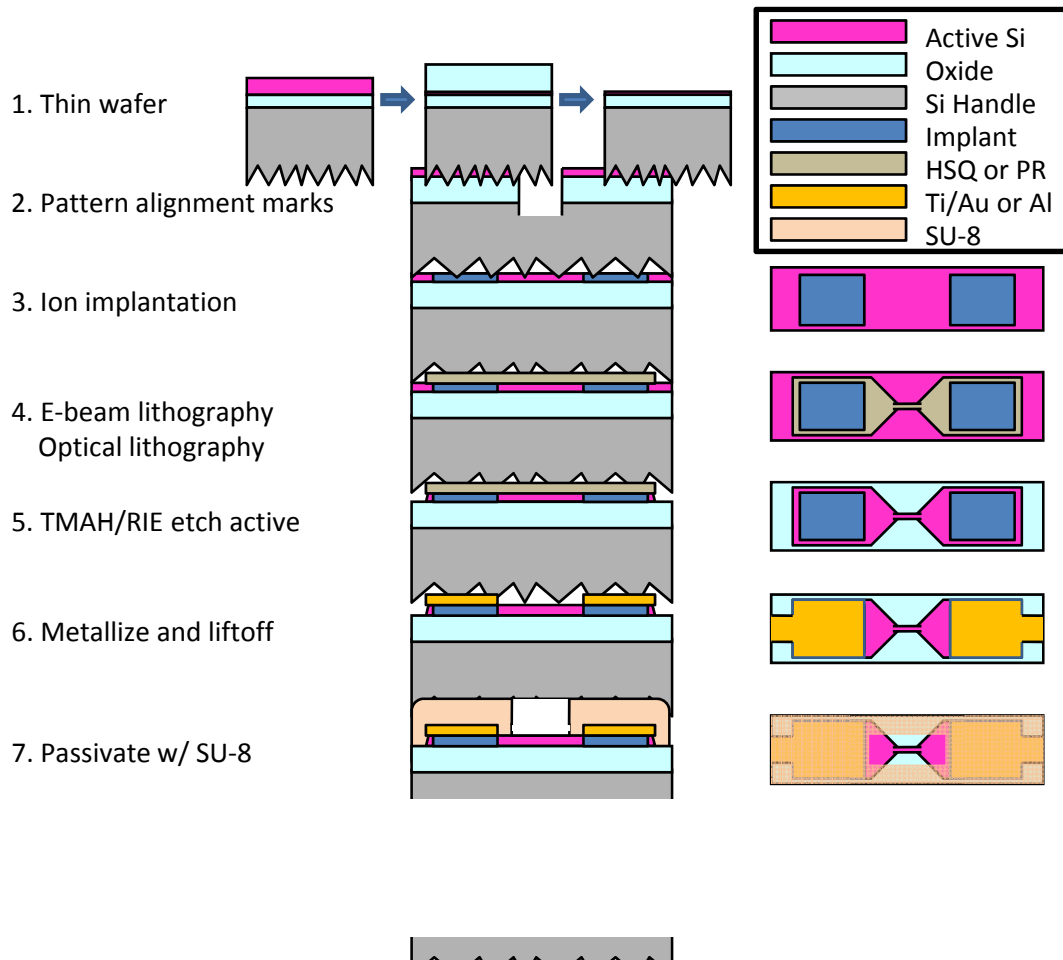
Progress: NW sensing chips for lipid bilayer

37 chips delivered

Summary of Devices Provided to UC Irvine

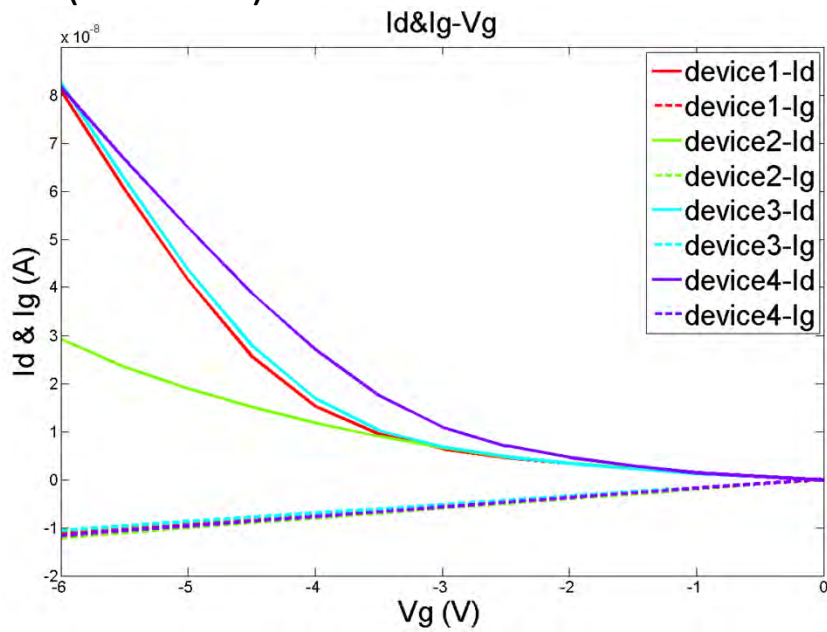
Batch #	Date	Chips	Purpose
Batch 1	08/05/13	(1) SiO ₂ , packaged	Ensure/test compatibility with new setup
Batch 2	07/01/14	(15) SiO ₂ , unpackaged, leaky	Establish SLB deposition protocol Test gate leakage suppression with/without SLB
Batch 3	03/21/14	(15) SiO ₂ , unpackaged, leaky	Establish SLB deposition protocol Test gate leakage suppression with/without SLB
Batch 4	08/06/14	(3) SiO ₂ , unpackaged, not leaky (3) Al ₂ O ₃ , packaged, not leaky	Test pH & ion sensitivity without/with SLB (Test functionalization on Al ₂ O ₃ vs. SiO ₂)

Fabrication flow

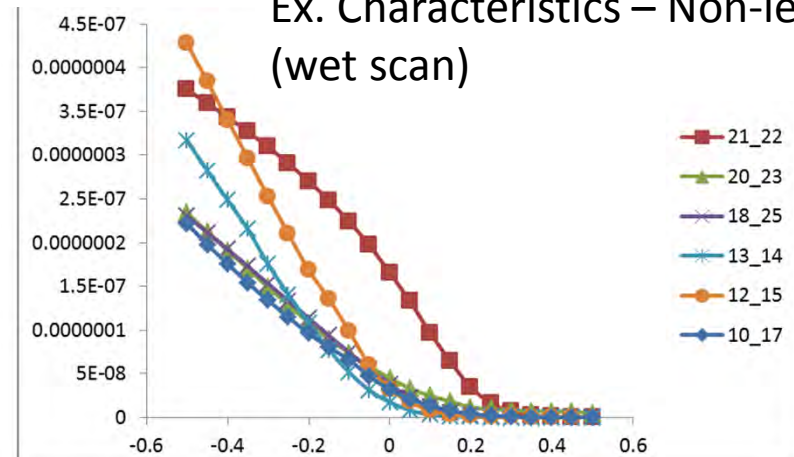


Device Characteristics

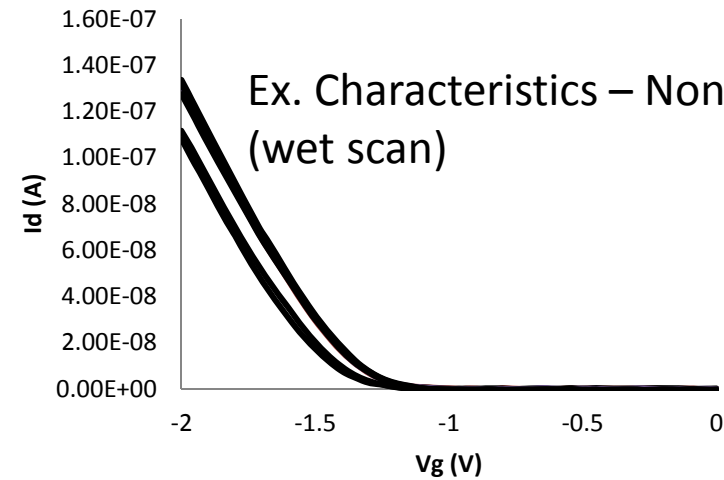
Ex. Characteristics – Leaky SiO₂
(wet scan)



Ex. Characteristics – Non-leaky Al₂O₃
(wet scan)



Ex. Characteristics – Non-leaky SiO₂
(wet scan)



UC Irvine Report

2/10/2014 - 8/6/2014

Carbon nanoelectronics (Test Bed II)
Nano-electrophysiology (Func. Scheme II)

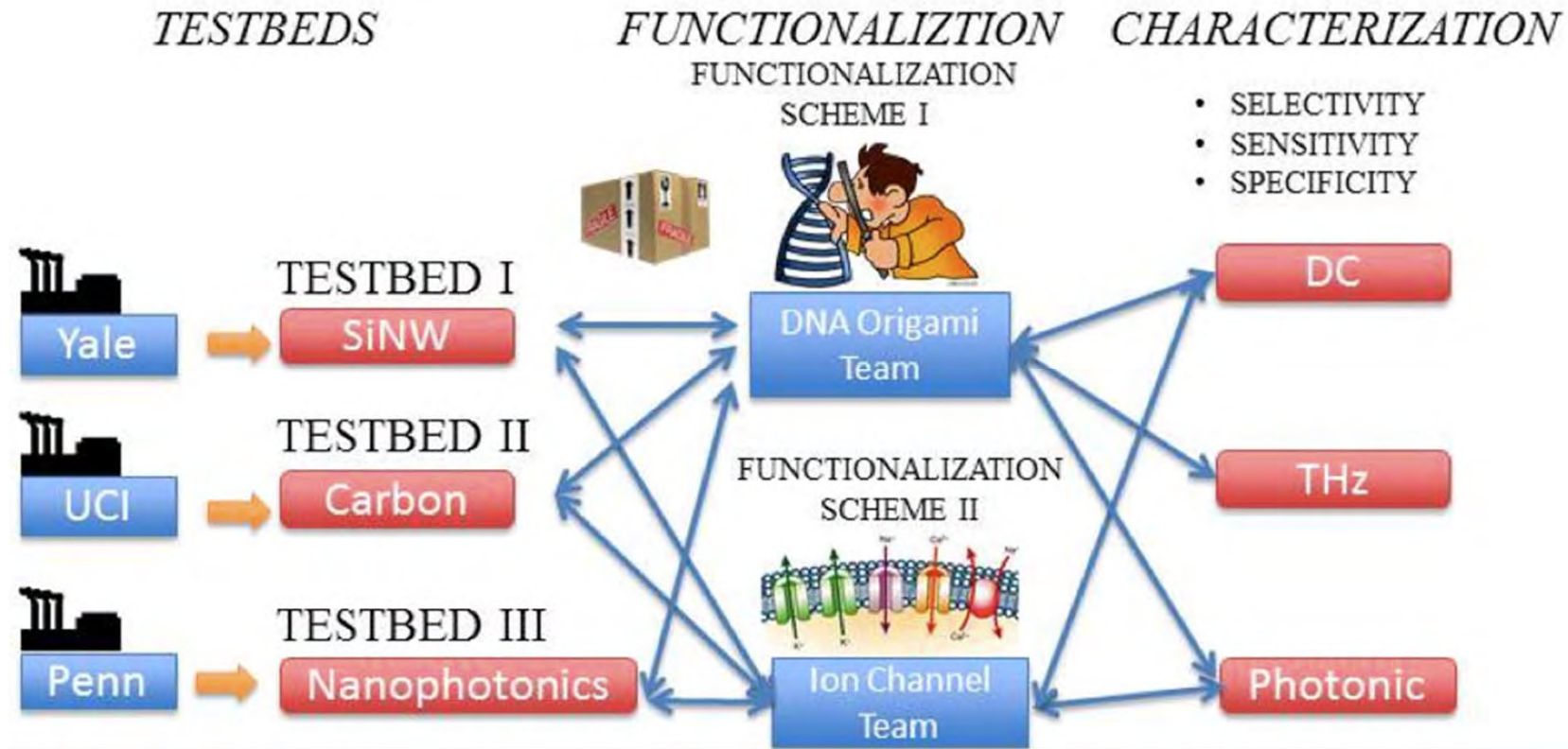
<http://www.burkelab.com/MURI/>

Peter Burke, Ph.D.
Department of EECS
Department of Biomedical Engineering
Department of Chemical Engineering and Materials Science
UC Irvine

UNIVERSITY of CALIFORNIA  IRVINE

MURI Award #W911NF-11-1-0024 (Start date 11/1/2010)

MURI Org Chart



Overview

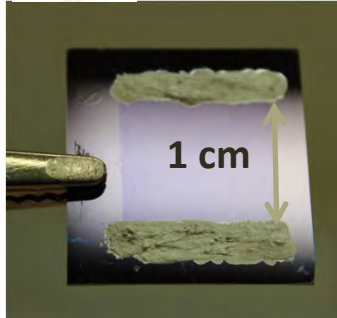
- Carbon nanoelectronics (Test Bed II)
 - All PDMS graphene testbed (2 batches to UIC for DNA aptamer functionalization)
 - Large area graphene for THz: Approaching the holy grail $Z_{\text{graphene}} < Z_0$
 - (2 batches to Wright, 1 joint paper submitted)
 - Graphene induced conformational change of DNA
(2 batches to Marshall for DNA origami func., 1 joint paper in preparation)
- Nano-electrophysiology (Func. Scheme II)
 - Non-covalent lipid bilayer – nanostructure integration
 - Carbon nanotube (2011-2014)
 - WW Zhou, Yung-Yu Wang, TS Lim, D. Jain and Peter J. Burke, "Detection of Single Ion Channel Activity with Carbon Nanotubes" *in preparation*
 - Graphene (2012-2013)
 - Yung-Yu Wang, Pham Ted, Katayoun Zand, Jinfeng Li, and Peter J. Burke, "Charging the Quantum Capacitance of Graphene with a Single Biological Ion Channel" *ACS Nano*, 8(5), 4228-4238 (2014)
 - Covalent lipid bilayer – nanostructure integration
 - Silane – oligo(PEG)- lipid attachment to SiO_2 (FRAP, EIS, protein insertion)
 - Carbon nanotube (single ion channel activity demonstrated)
 - Silicon nanowires (fluorescence shows functionalization successful)
 - Optical nanowire integration (future)

Carbon nanoelectronics (Test Bed II)

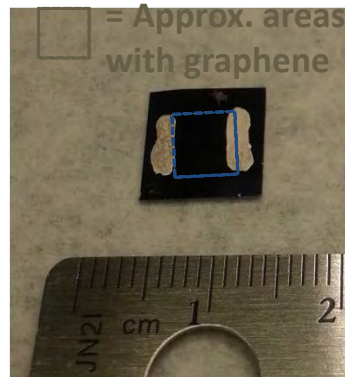
Test Bed II Carbon Electronics



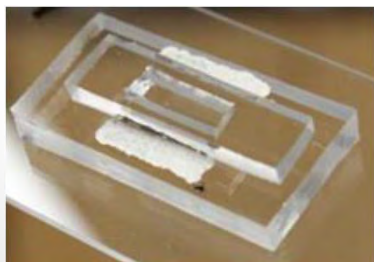
UCI Graphene Samples



Substrate: High Resistivity 90nm SiO₂
 Graphene Size: ~ 1cm x 1cm (Large Area)
 Transfer Method: PMMA Wet Transfer
 Processing: Acetone wash +
 400° C anneal in 1:1 H₂:Ar
 Notes: Gating, large area



Substrate: Mica
 Graphene Size: ~ .6cm x .6cm
 Transfer Method: PMMA Wet Transfer
 Processing: Acetone wash +
 400° C anneal in 1:1 H₂:Ar
 Notes: Gating, smooth & clean surface



Substrate: PDMS with PDMS well
 Graphene Size: ~ 1cm x 1cm (Large Area)
 Transfer Method: Direct Transfer
 Processing: DI water wash and dry
 Wang, Burke *Appl. Phys. Lett.* 103 (2013)

Graphene improvement goals:

- Achieve $Z_{\text{graphene}} < Z_0$
- Large area gated graphene (cm²) for THz modulator

(Neither has been achieved in literature)

Before Feb: 3 Batches
 26 Samples

Since Feb: 2 Batches
 16 Samples



THz measurement

Before Feb: 2 Batches
 13 Samples

Since Feb: 2 Batches
 5 Samples



DNA functionalization

Back to UCI

Before Feb: 4 Batches
 8 Samples

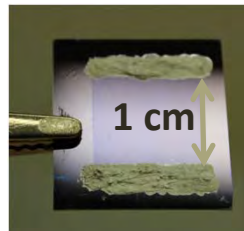
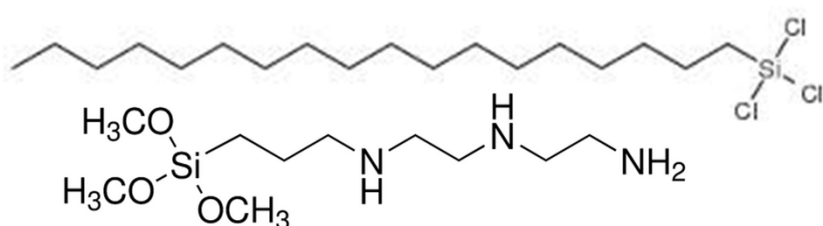
Since Feb: 2 batches
 15 Samples



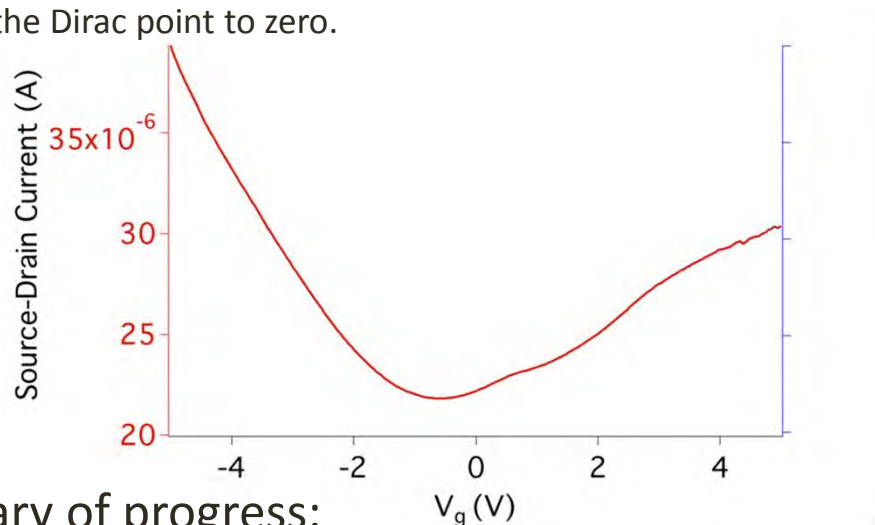
Aptamer functionalization

Improved Graphene Transfer

Self-assembly of silane on substrates with different end functional groups prior to transfer



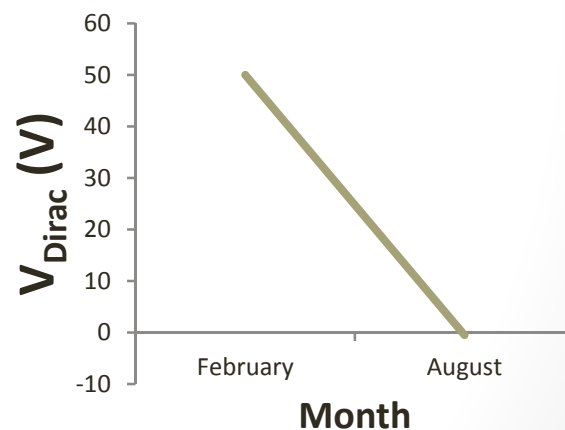
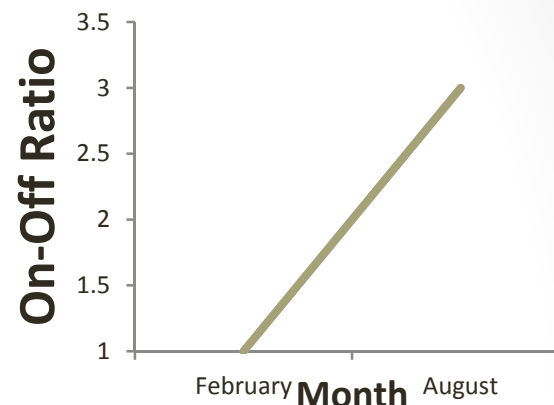
Mixed silanes of Octadecyltrichlorosilane (OTS) and N1-(3-Trimethoxysilylpropyl)diethylenetriamine to delicately tune the Dirac point to zero.



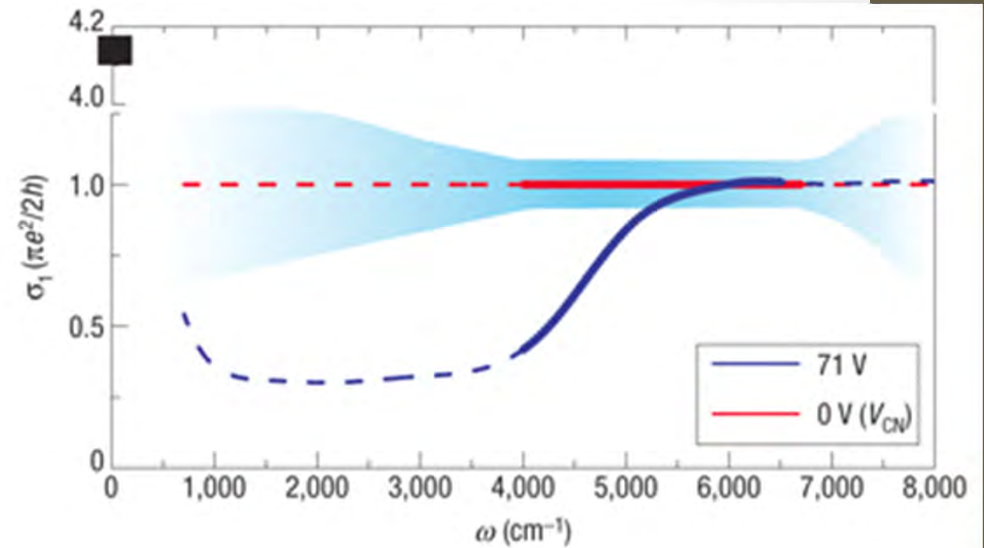
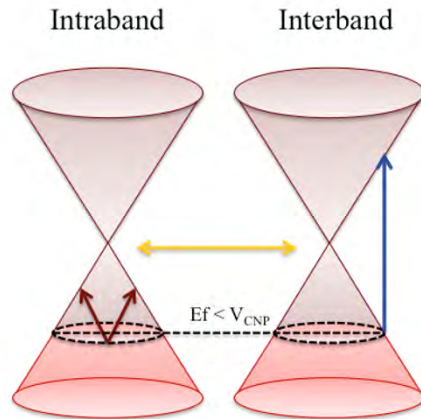
Summary of progress:

- Large area graphene (cm^2 size)
- High On-Off ratio
- Dirac point near zero

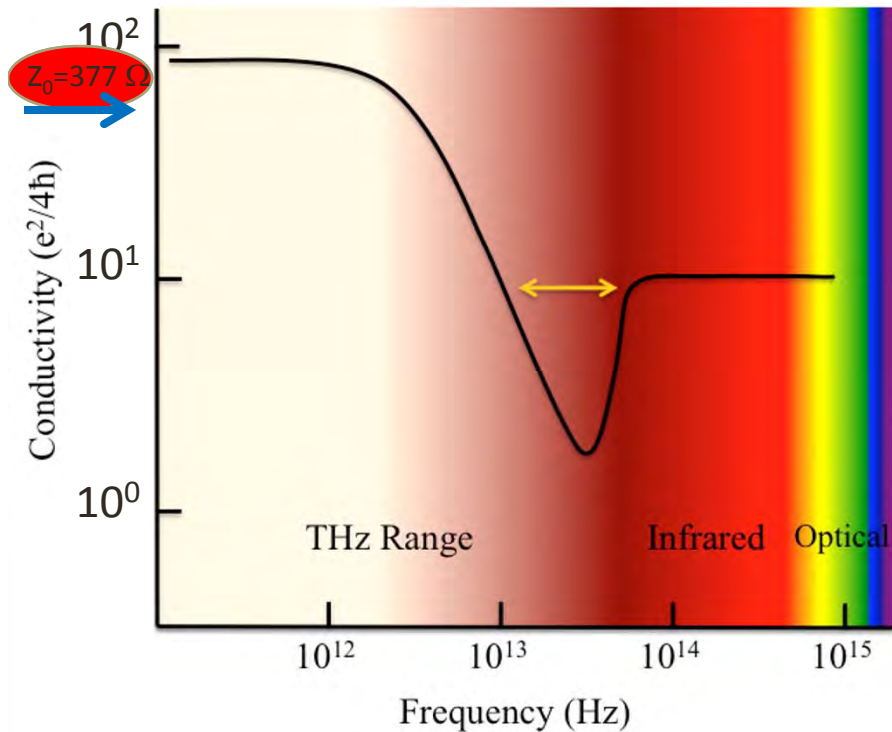
Significance: Never achieved before over such a large area (cm^2), needed for THz graphene optics.



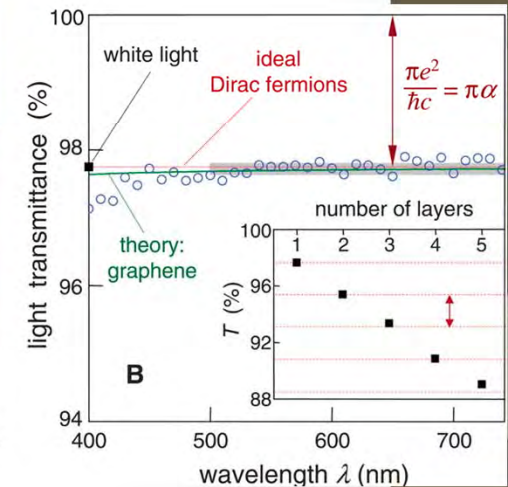
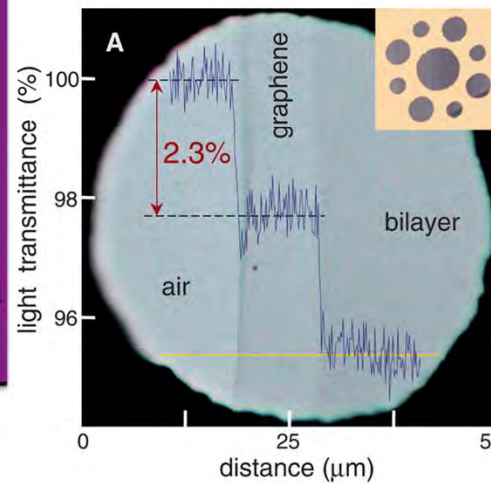
Graphene as a tunable electromagnetic material



Z. Q. Li, E. A. Henriksen, Z. Jiang, Z. Hao, M. C. Martin, P. Kim, H. L. Stormer, D. N. Basov *Nature Physics* (2008)

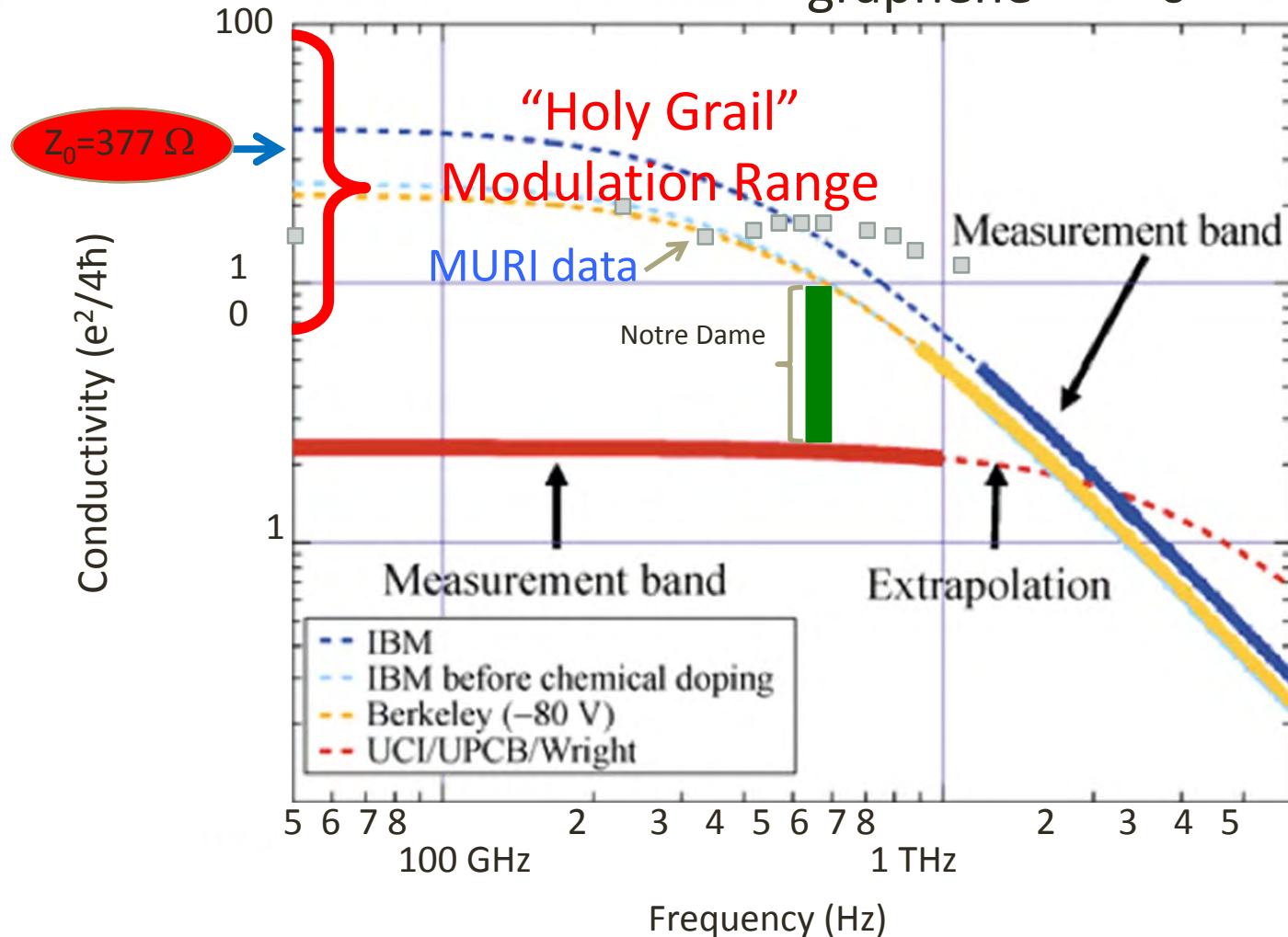


Zhang, Pham, Brown, Burke, *submitted* (2014)



R. R. Nair, P. Blake, A. N. Grigorenko, K. S. Novoselov, T. J. Booth, T. Stauber, N. M. R. Peres, A. K. Geim *Science* (2008)

Towards the Holy Grail: $Z_{\text{graphene}} < Z_0 = 377 \Omega$



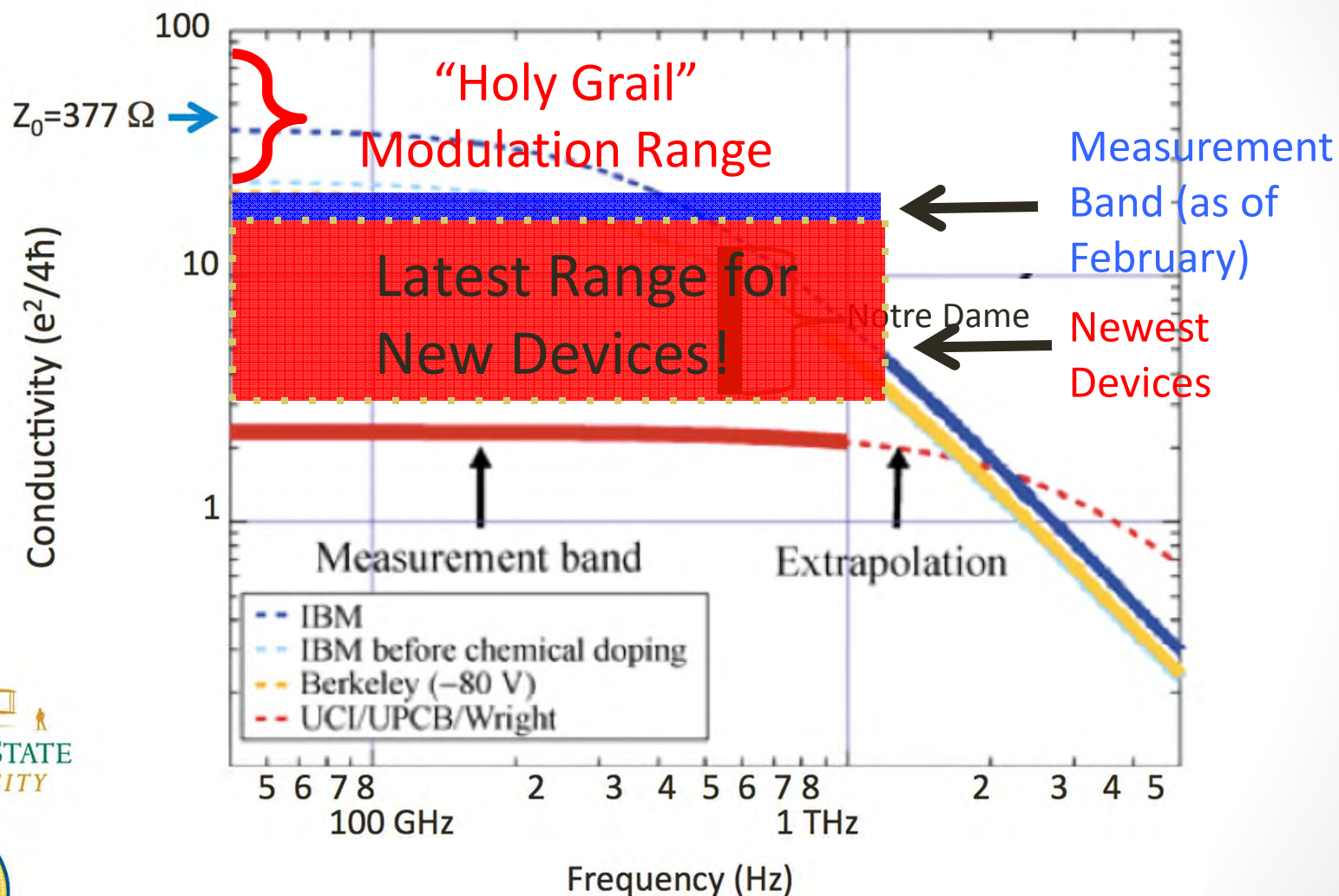
Zhang, Pham, Brown, Burke, *submitted (2014)*

Rouhi, N., Capdevila, S., Jain, D., Zand, K., Wang, Y. Y., Brown, E., L. Jofre, Burke, P. *Nano Research (2012)*

Sensale-Rodriguez, B., Yan, R., Rafique, S., Zhu, M., Li, W., Liang, Sensale-Rodriguez, B., Yan, R., Kelly, M. M., Fang, T., Tahy K., Hwang, W.S.,

Significance: First nanomaterial manipulation of THz with perfect impedance match to free space.

Towards the Holy Grail: $Z_{\text{graphene}} < Z_0 = 377 \Omega$



Rouhi, N., Capdevila, S., Jain, D., Zand, K., Wang, Y. Y., Brown, E., L. Jofre, Burke, P. *Nano Research* (2012)

Sensale-Rodriguez, B., Yan, R., Rafique, S., Zhu, M., Li, W., Liang, Sensale-Rodriguez, B., Yan, R., Kelly, M. M., Fang, T., Tahy K., Hwang, W.S., X., Xing, H. G. *Nano Letters*, (2012)

Jena, D., Liu, L., Xing H.G. *Nature Communications* (2012)

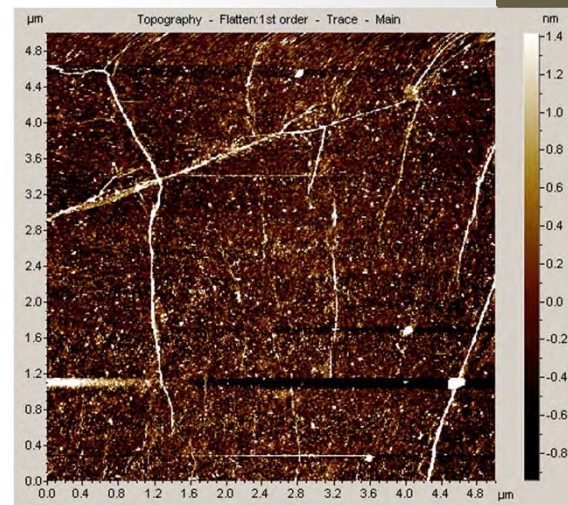
DNA Origami on Graphene

UCI

Marshall

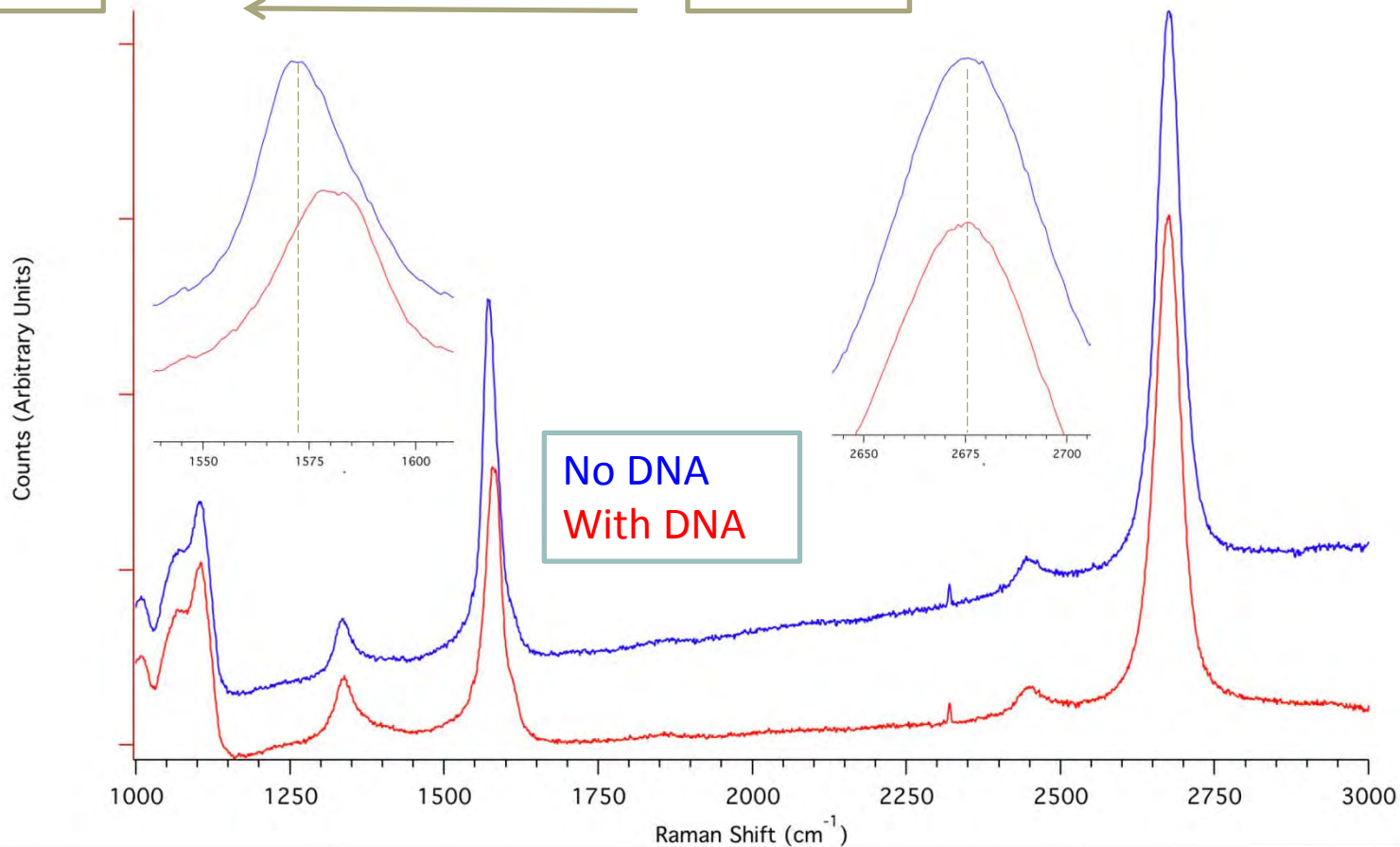
May – July
5 Samples
Graphene on Mica

DNA Origami
Deposited on
Graphene



UCI

Marshall

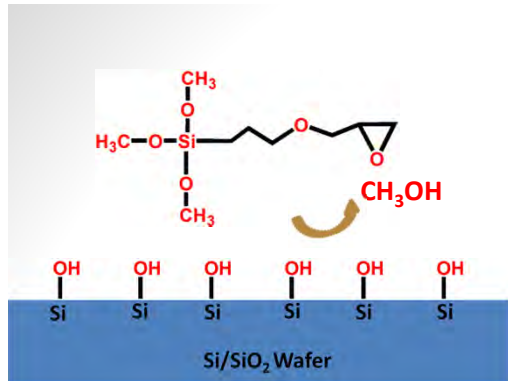


Functionalization Scheme II: Nano-electrophysiology

Silane – oligo(PEG)- lipid
attachment to SiO_2
(Func Scheme II on Test bed I,II,III)

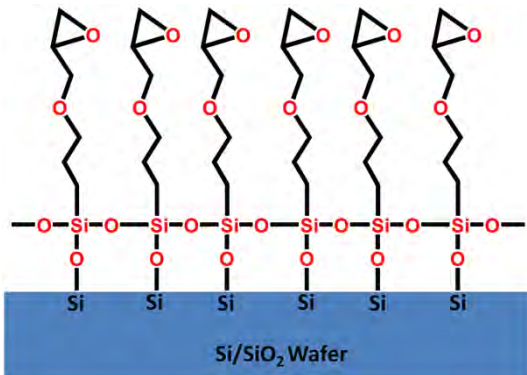
Lipid bilayers on SiO₂

Successfully demonstrated before 2/2014

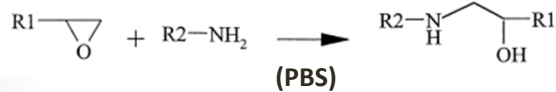


Step1

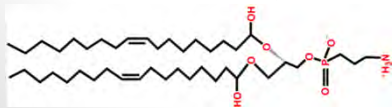
Self-assembly of silane
Hydrolysis reaction in ethanol



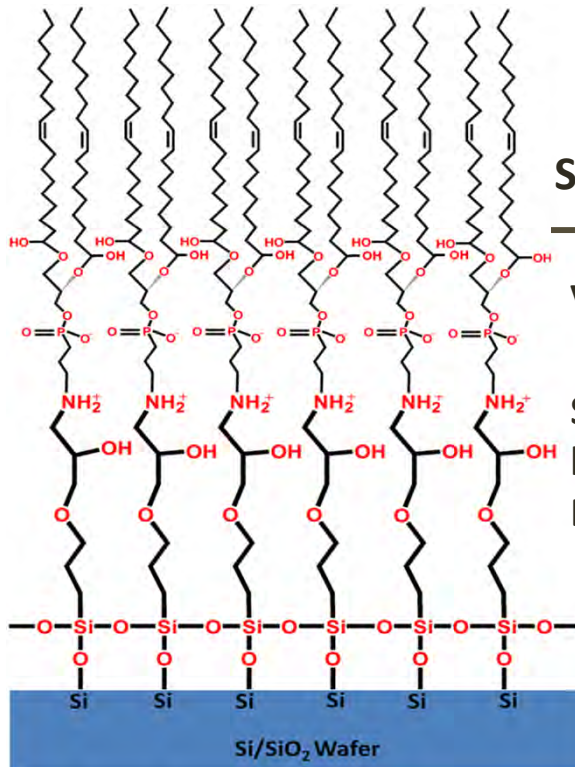
Step2



Tether first layer DOPE lipid

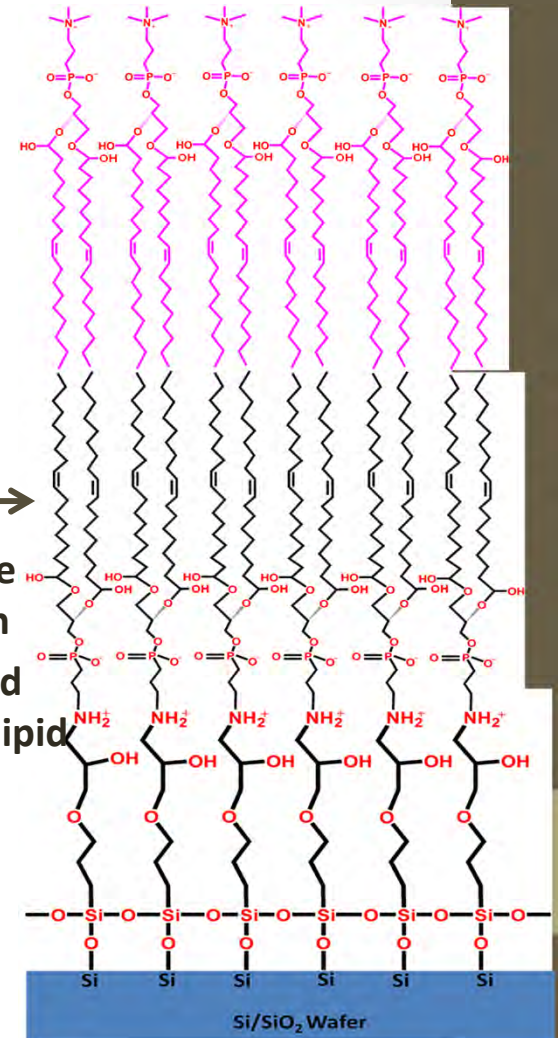


- No need synthesize chemicals
- Easy fabrication



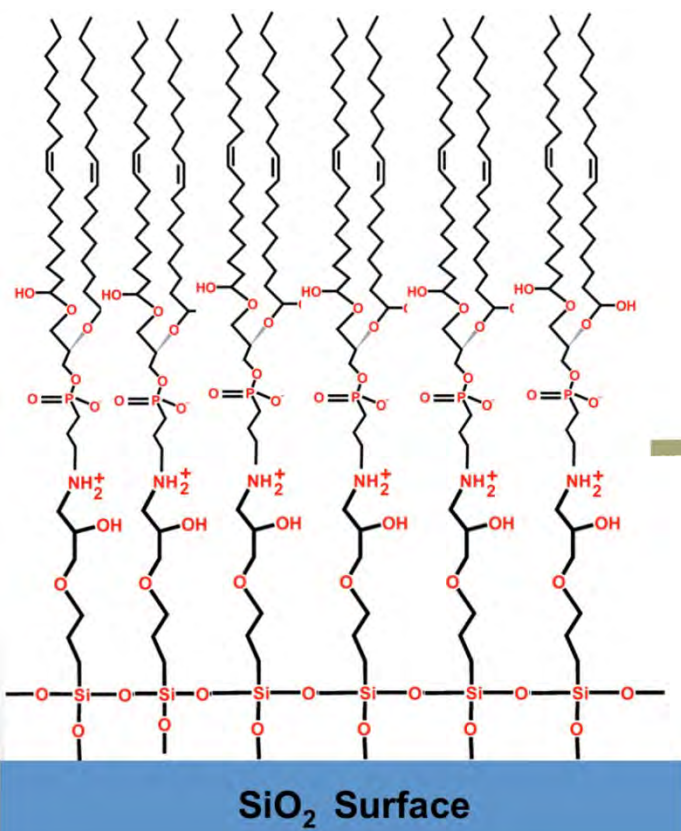
Step3

Vesicle fusion
Second layer lipid
DOPC

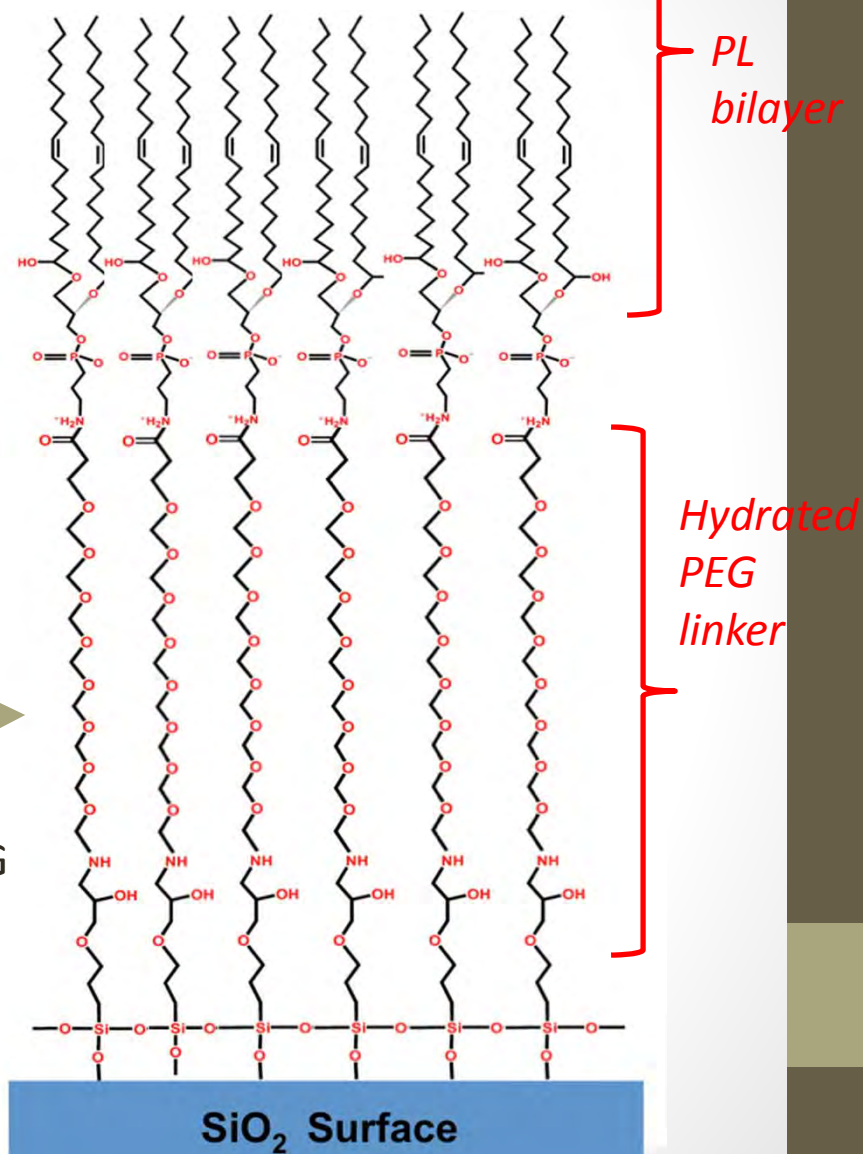
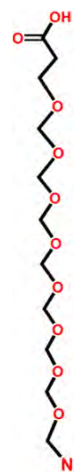


Proposed modification to covalent tether

PEG spacer (3nm) for thicker hydrated layer



3.3 nm length
8 unit oligo-PEG

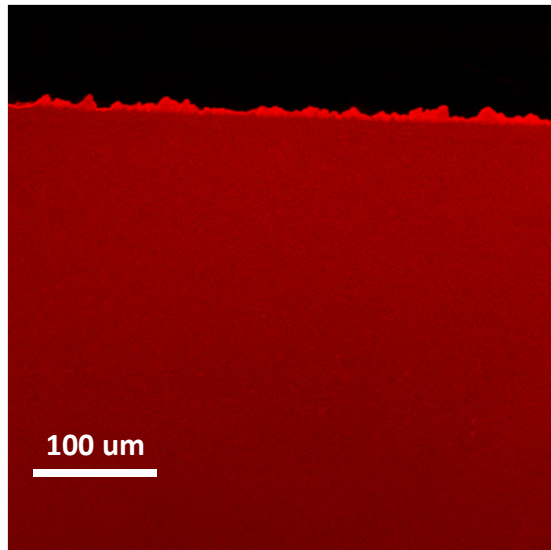


Successful Silane-oligo(PEG)-PL bilayer tether

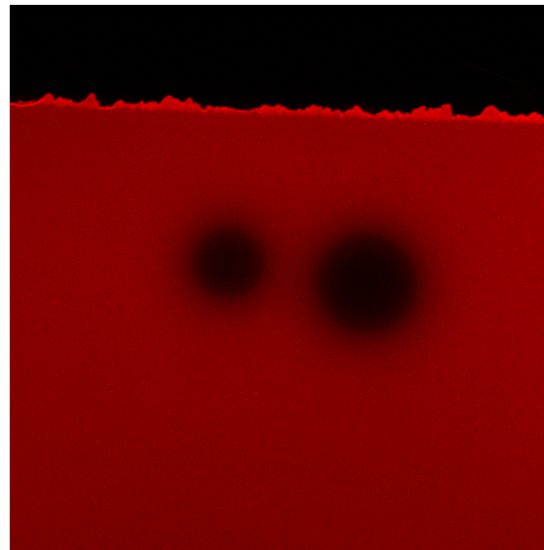
10 iterations of recipe optimization during last 6 months

Fluorescence Image

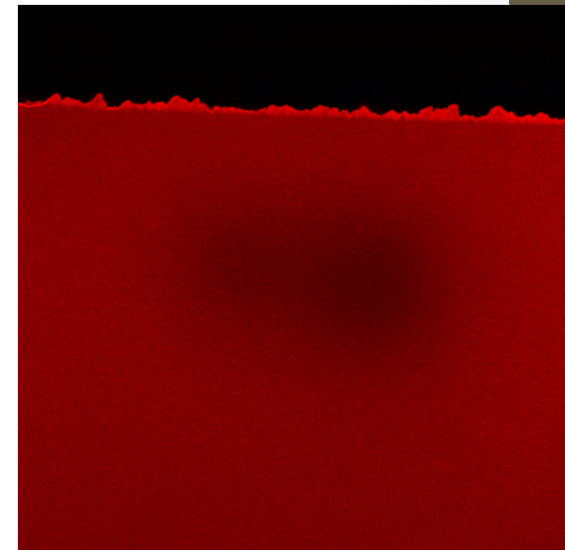
Before bleaching



After bleaching (t=0)



After recovery (t=9 min)

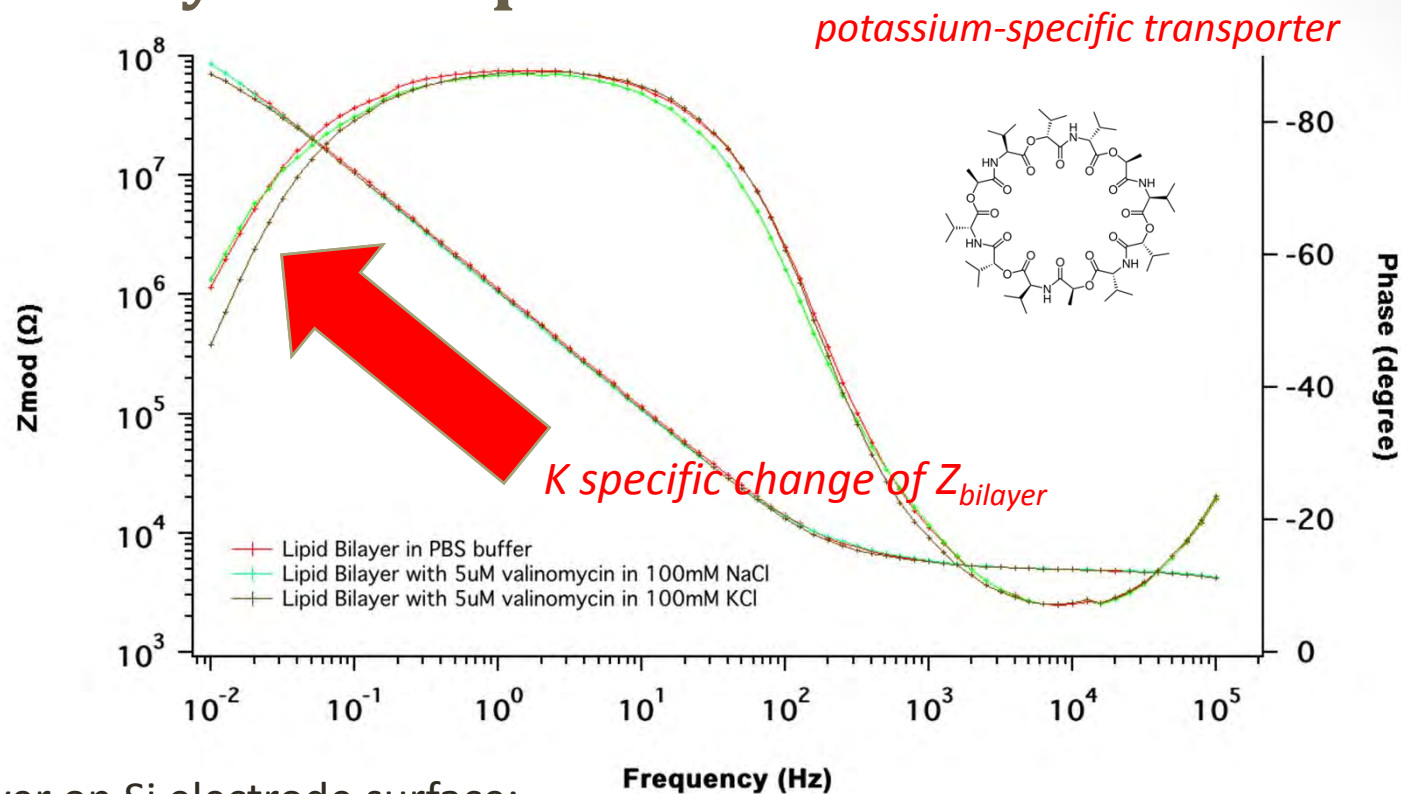


Tethered lipid bilayer on glass cover slide surface.

Diffusion coefficient: $D = R^2/4t_{50}$

R is radius of the photobleaching area and t_{50} is the time required to achieve 50% fluorescence intensity recovery. So D is $\sim 1.1 \mu\text{m}^2 \cdot \text{s}^{-1}$, which is higher than without peg spacer result ($0.99 \mu\text{m}^2 \cdot \text{s}^{-1}$), indicating longer tether molecular has better bilayer fluidity.

Valinomycin incorporation



Monolayer on Si electrode surface:

$R = 0.3 \text{ M}\Omega \text{ cm}^2 - 1 \text{ M}\Omega \text{ cm}^2$ $C = 1.2 \text{ }\mu\text{F/cm}^2 - 2 \text{ }\mu\text{F/cm}^2$

Bilayer on Si electrode surface:

$R = 0.5 \text{ M}\Omega \text{ cm}^2 - 2 \text{ M}\Omega \text{ cm}^2$ $C = 0.6 \text{ }\mu\text{F/cm}^2 - 1.5 \text{ }\mu\text{F/cm}^2$.

Valinomycin decreases R for KCl only, not NaCl, as expected.

Significance: Covalent tethered PL bilayer on oxide with membrane protein incorporation: A general scheme.

Future work: Extend to Test Beds I,II,II.

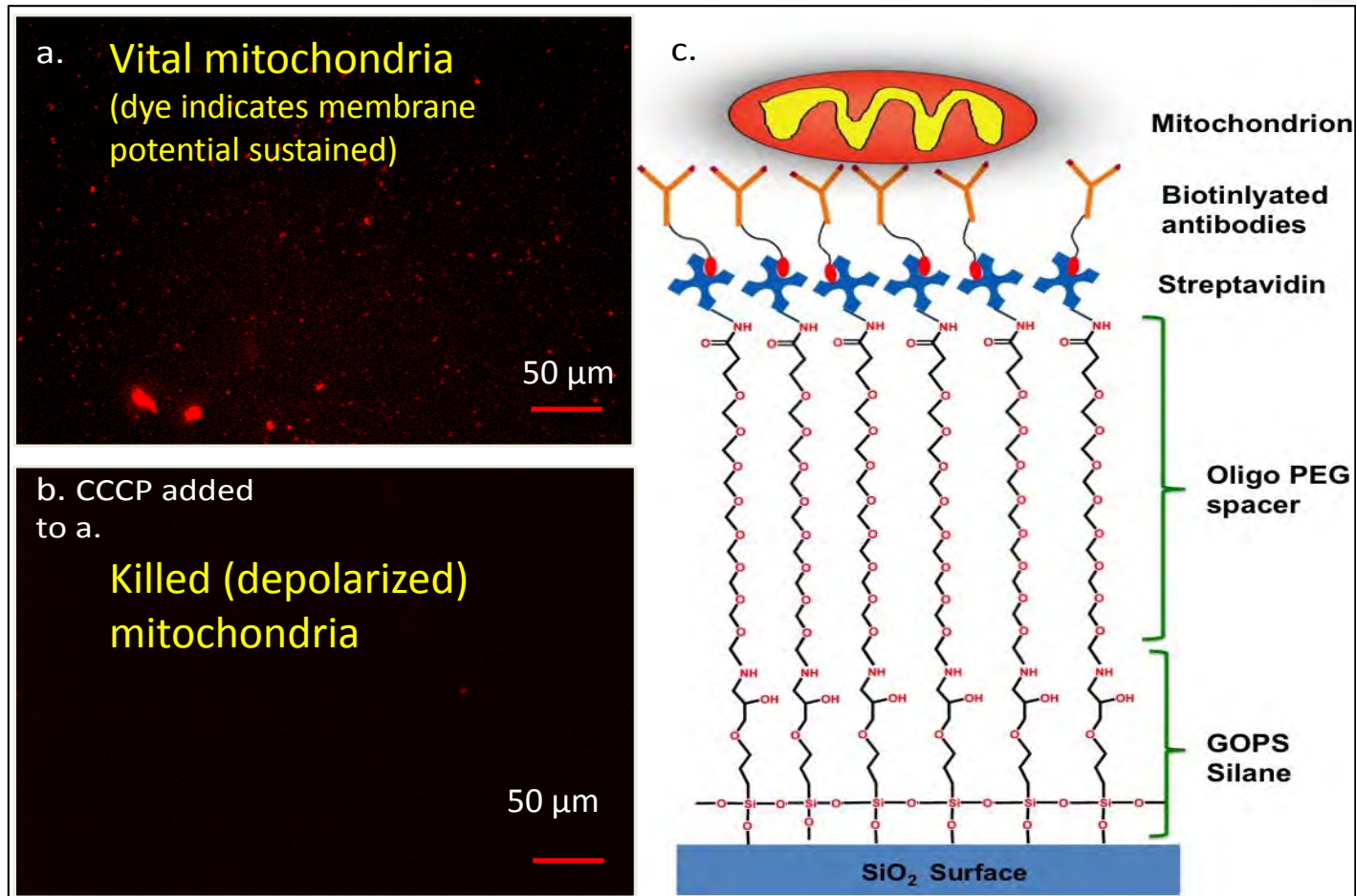
Significances:

- Hydrophilic spacer can lift lipid bilayer membrane up from the substrate for preventing transmembrane protein de-active and supporting ion transport cross membrane.
- Longer tethered lipid is more flexible and then has higher lateral fluidity, which can enhance membrane protein incorporation .
- Larger hydrated reservoir can host more water and reduce the possibility of ion saturation.

Future Plan:

- Characterize tethered lipid structure using synchrotron x-ray reflectometry.
- Try to functionalize other type oxide/metal electrodes (such as TiO₂/Ti, Y₂O₃/Y, Al₂O₃/Al and ITO).

Leverage project (National Cancer Institute): Mitochondria Purification and Immobilization on Chip



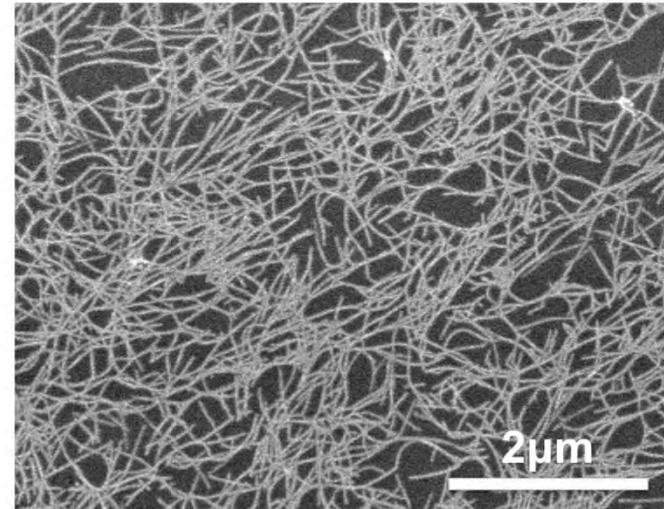
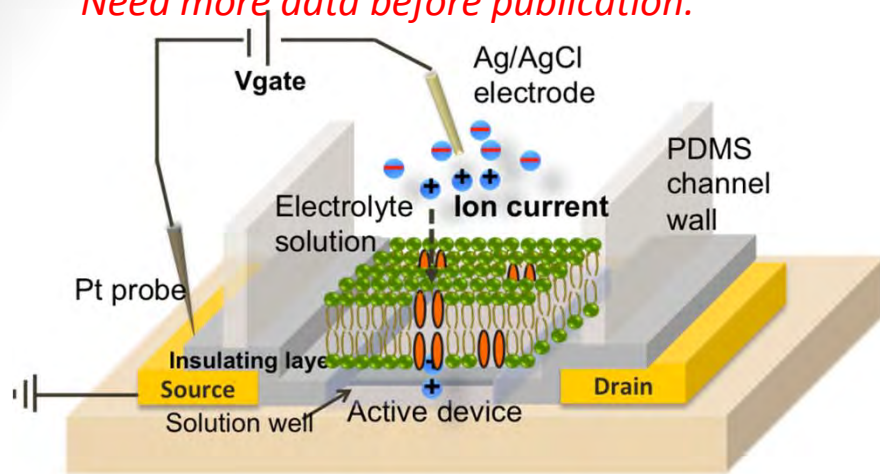
Significance: Method to purify vital mitochondria from cell lysates without need for centrifuge.

Lipid bilayers on Carbon Nanotubes (Func Scheme II on Test bed II)

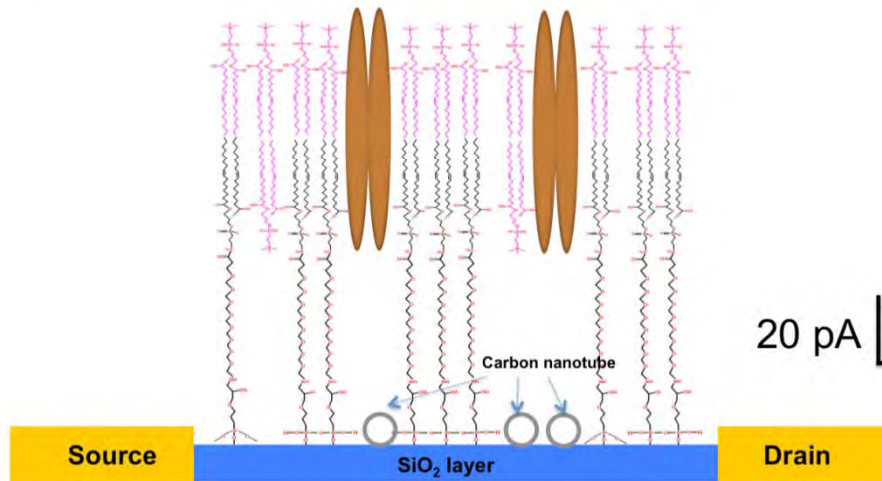
Ion Channel Activity Measurement

Proof of concept demonstrated.

Need more data before publication.



Carbon nanotube network

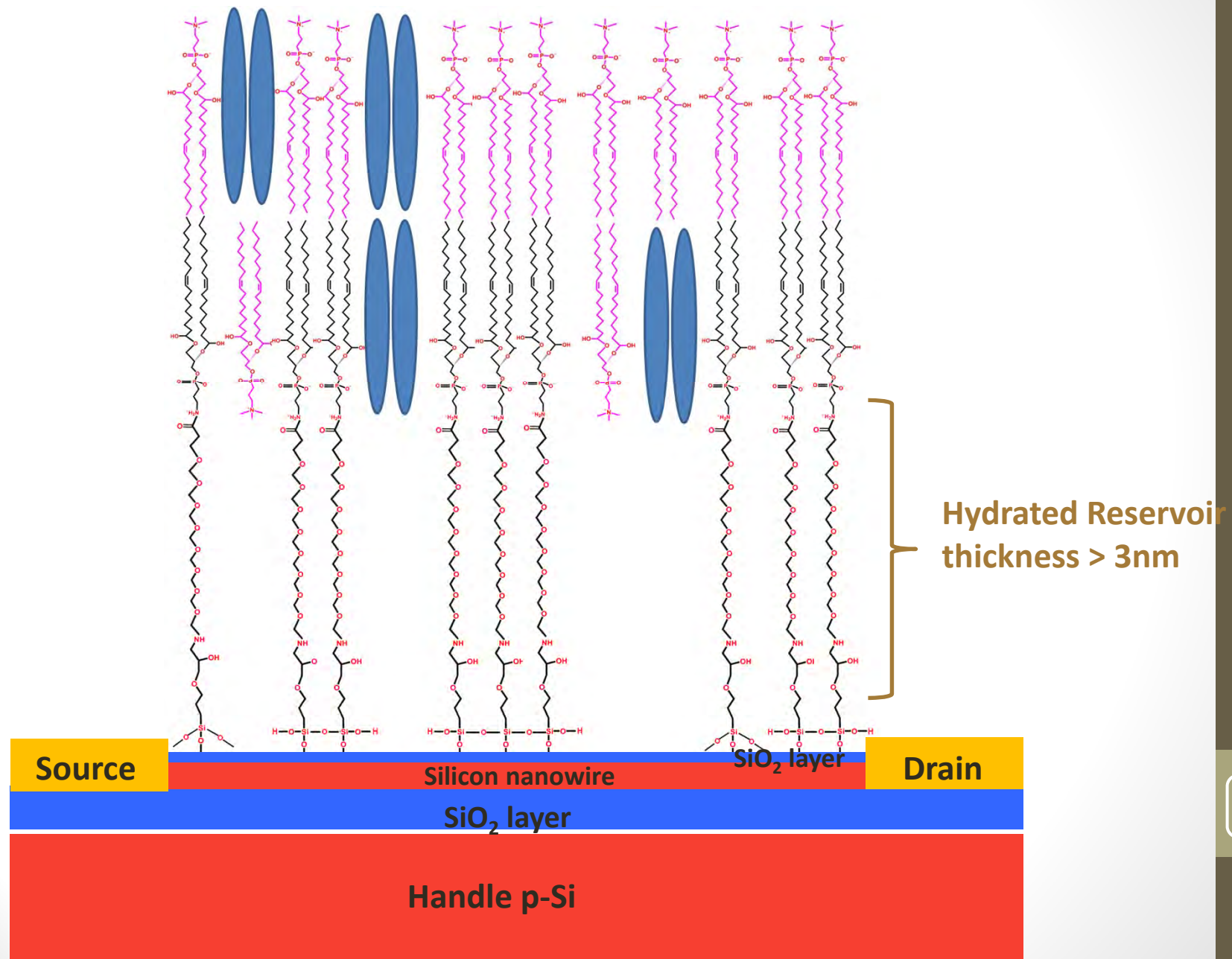


Current trace shows single pore fluctuations induced by the incorporation of alamethicin into the lipid membrane on CNT transistor

Significance: Single ion channel interrogation with carbon nanotubes using with covalently attached lipid bilayers.

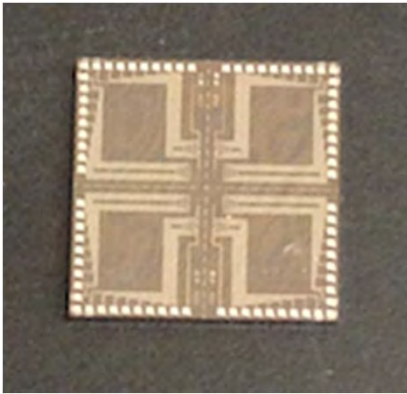
Lipid bilayers on Silicon Nanowires (Func Scheme II on Test bed I)

Goal: Lipid functionalized SiNW



Progress: SiNW Chips from Yale

3rd batch were shipped to UCI by March 21 2014

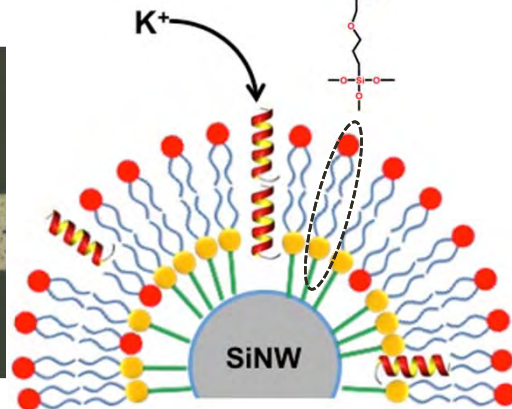
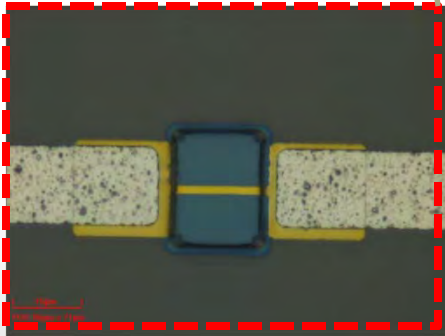
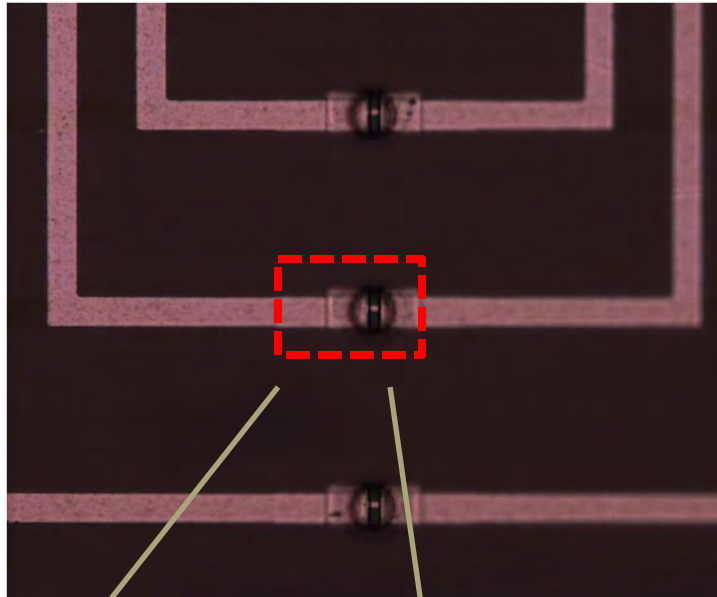


- Chip Size: 6 × 6 mm
- Chip number : 15
- 3 chips are used for depositing SLBs test(11-02, 11-03, 11-05)
- 2 chips are used for liquid gate test(07-17, 09-13)
- 9 chips fail in glue test (11-11, 11-13, 11-17, 09-11, 09-15, 09-17, 09-23, 09-25, 07-25)
- 1 chip left(09-03)

4th batch shipped to UCI August 2014

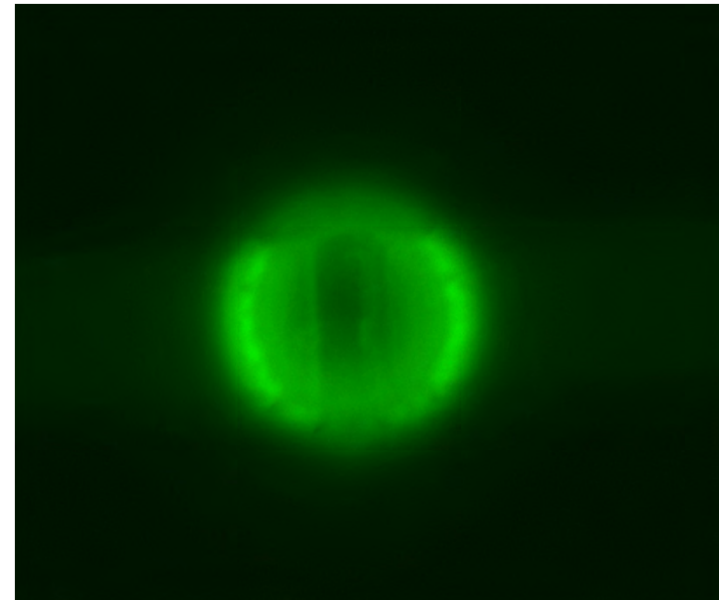
- Lower threshold voltage to avoid lipid bilayer damage at high V_{gate}

Silicon Nanowire Successfully Functionalized with Tethered Lipids!



Method I:

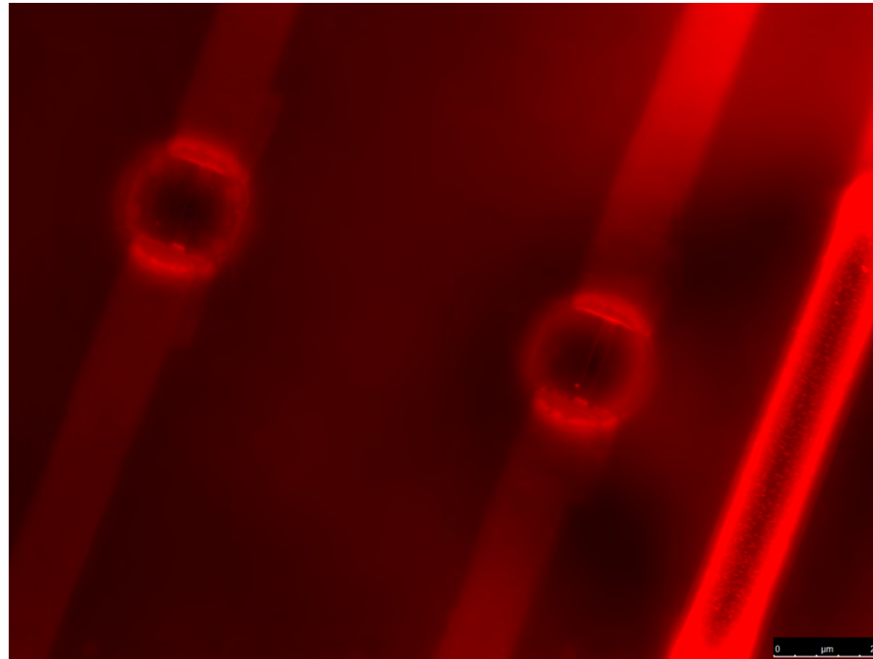
- One-day water soaking to generate hydroxyl group on silicon nanowire surface.
- Bottom-up approach to layer-by-layer grow silane film, oligo(ethylene glycol) spacer and lipid on Si NW (Details are same as Si wafer functionalization).
- Use vesicle fusion to put second floating lipid with dye molecular.



Method II:

Using O₂ plasma (50watt, 1min) to treat chip surface for generating surface hydroxyl group.

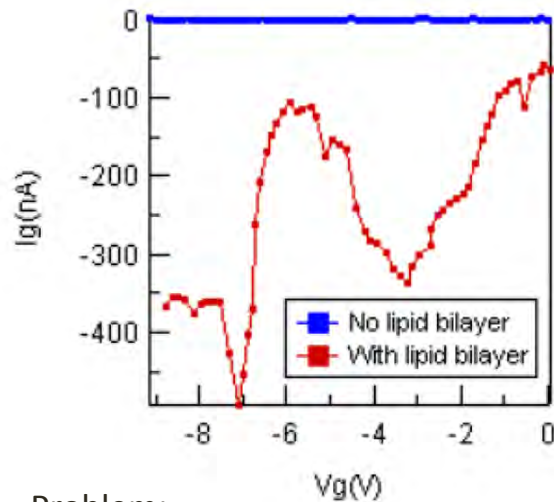
Problem is lipid covers all surface not only in the well.



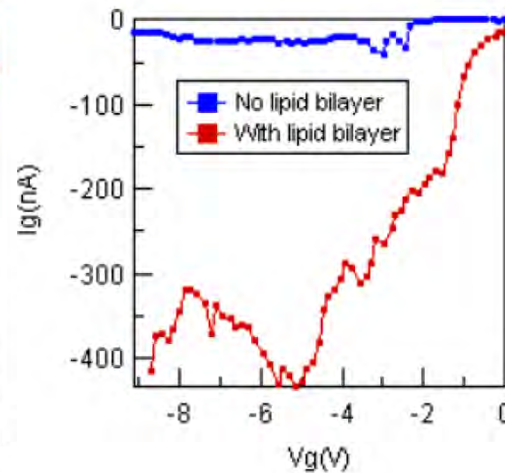
Challenges

1) Passivation layer damage

Device 1



Device 2



Problem:

- SU8 may be damaged during functionalization process, exposing electrodes...

Solution:

- Adjust functionalization procedure (minor challenge)

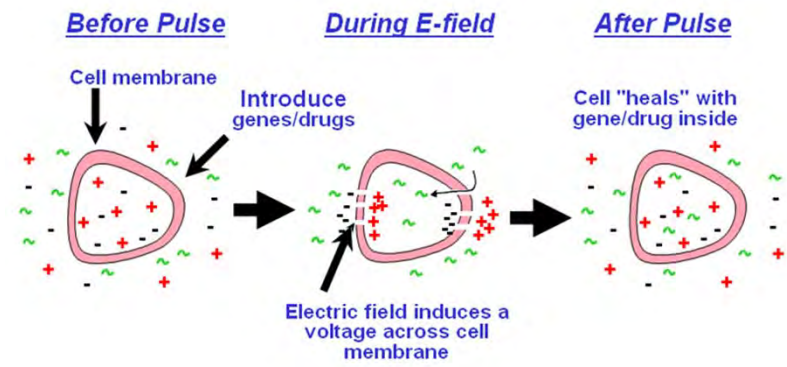
2) Lipid bilayer damage (electroporation)

Problem:

- Lipid bilayers damaged at 0.25 V
- SiNW threshold voltage -8 V

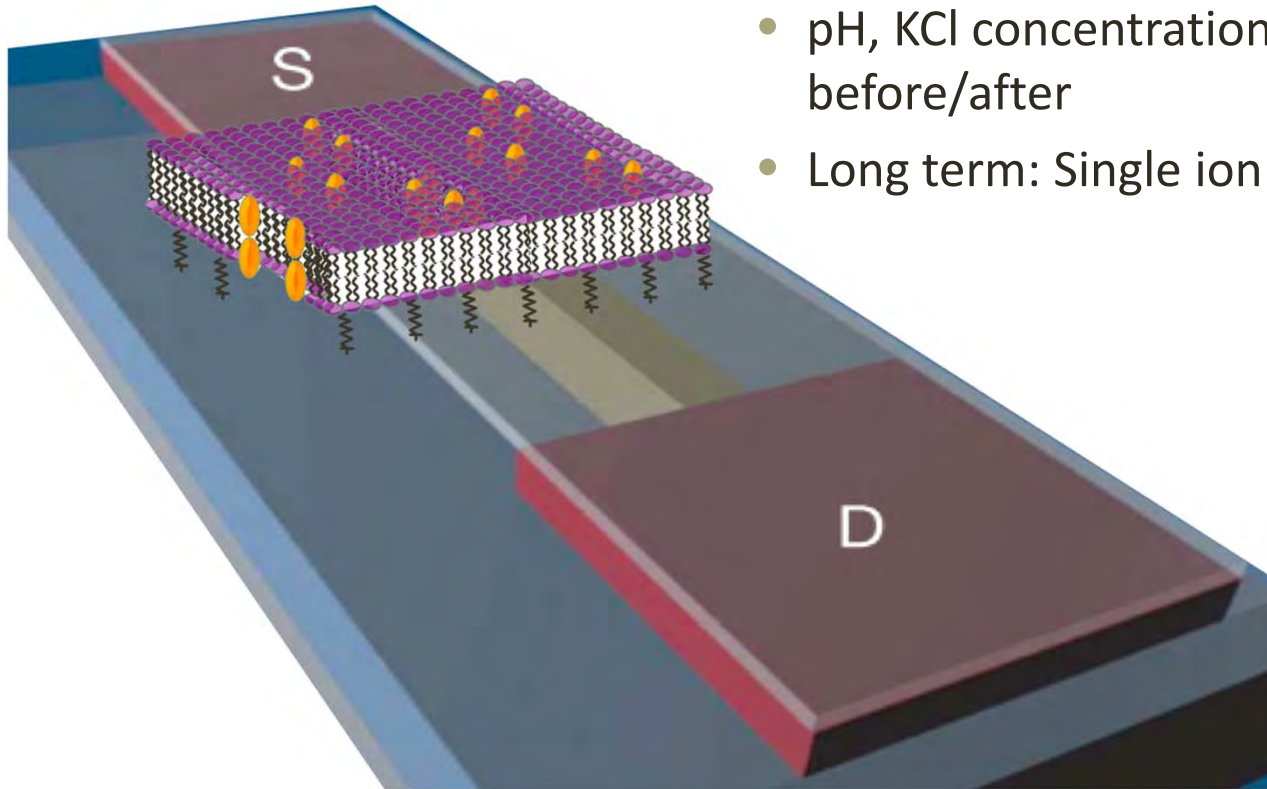
Solution:

- Measure sub-threshold current @ 0.25 V
- Adjust SiNW threshold voltage (empirical)



Silicon nanowire next steps

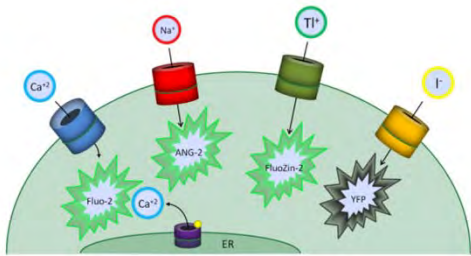
- Threshold voltage and leakage current before/after lipid bilayer deposition
- pH, KCl concentration dependence before/after
- Long term: Single ion channel activity



Lipid bilayers on Optical Nanowires (Func Scheme II on Test bed III)

Optical Nanowires & Optogenetics

Ion sensitive flourophores

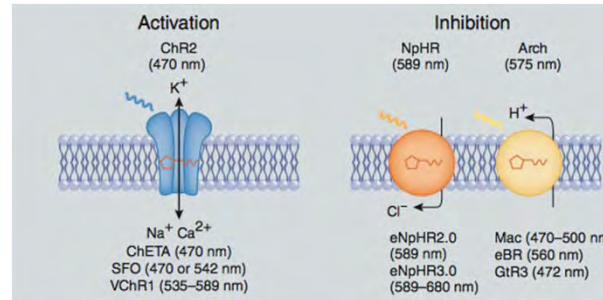


1. McManus, O. B., Garcia, M. L., Weaver, D., Bryant, M., Titus, S., & Herrington, J. B. Ion Channel Screening. 2004.

Applications:

- Nanowire photon emitter/detector for local (nanoscale) ionic concentration assay

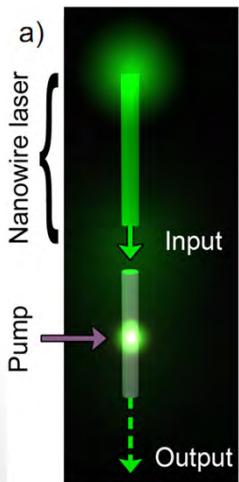
Light-gated Ion Channels: Optogenetics



Pastrana, Nature Methods **8**, 24-25 (2011)

Type	Ions
Channelrhodopsin	Cations (non selective)
Halorhodopsin	Chloride
Archaeorhodopsin	Proton
Bacteriorhodopsin	Proton

Nanowire Emitter/Detector



Agarwal, Penn

Initial steps (planned w/Penn):

- Threshold voltage and leakage current before/after lipid bilayer deposition of Penn NW
- Light modulated single ion channel activity
- Locally trigger ion channels (optically)
- Locally detect light from ion channels
- Modulate membrane potentials
- Selectively fire neurons

Publications & Presentations

Journal Articles under #W911NF-11-1-0024

*1. W.W. Zhou, Y. Wang, T.S. Lim, D. Jain, P. Burke

“Detection of single ion channel activity with carbon nanotubes”, *in preparation* (2014).

*Since last review
(2/2014)*

*2. W.W. Zhou, P. Burke

“Bottom-up Approach to Synthesize Tethered Lipid Bilayer Membranes on SiO₂ Surface for Ion-Channel Biosensor Application” *in preparation* (2014).

*3 Weidong. Zhang, Elliot. R. Brown, Phi Pham, Yung Yu Wang, Peter J. Burke. (submitted)
AC Conductivity Parameters of Graphene Derived from THz Etalon Transmittance.

*4. Yung Yu Wang, Ted Pham, Katayoun Zand and Peter J. Burke.

“Charging the Quantum Capacitance of Graphene with a Single Biological Ion Channel”
ACS Nano, 8(5), 4228-4238 (2014)

*5. Yung Yu Wang and Peter J. Burke.

“Polyelectrolyte Multilayer Electrostatic Gating of Graphene Field-Effect Transistors”, *Nano Research* (*in press*)

6.. Katayoun Zand, Ted Pham, Antonio Dávila Jr, Douglas C. Wallace and Peter J. Burke.

“Nanofluidic Platform for Single Mitochondria Analysis Using Fluorescence Microscopy”
Analytical Chemistry, 2013, 85, 6018, DOI: 10.1021/ac4010088

7. Nima Rouhi, Yung Yu Wang, Peter J. Burke.

“Ultrahigh Conductivity of Large Area Suspended Few Layer Graphene Films”,
Applied Physics Letters, 2012, 101, 263101, DOI: 10.1063/1.4772797

8. N. Rouhi, S. Capdevila, D. Jain, K. Zand ,Y. Wang, E. Brown, L. Jofre, P. Burke.

“Terahertz Graphene Optics”, *NanoResearch*, 2012, DOI: 10.1007/s12274-012-0251-02

9. Tae-Sun Lim, Antonio Davila Jr, Katayoun Zand, Douglas C. Wallace, Peter J. Burke.

“Wafer-scale Mitochondrial Membrane Potential Assays”, *Lab Chip*, 2012, DOI: 10.1039/c2lc40086c

10.Nima Rouhi, Dheeraj Jain, and Peter John Burke.

"High Performance Semiconducting Nanotube Inks: Progress and Prospects", *ACS Nano*, 2011,
DOI: 10.1021/nn201828y

Conference Presentations under #W911NF-11-1-0024

- *1. Peter Burke "Towards a Single Cell Radio" , ACM NANOCOM, May 13 – 14, 2014, Atlanta, Georgia.
 - *2. Phi Pham “Broadband Measurement of Terahertz Transmission Modulation Using Back-Gated Graphene”, MRS Spring meeting 2014, April 2014, San Francisco, CA.
 - *3. Weiwei Zhou “Integration of Carbon Nanotube Network Transistor and Tethered Lipid Bilayer on SiO₂ surface for Single-Ion Channel Recording”, MRS Spring meeting 2014, April 2014, San Francisco, CA. (poster presentation).
 - *4. Ted Pham “ Charging the Quantum Capacitance of Graphene with a Single Biological Ion Channel” UC System wide Bioengineering Symposium, June 2014, Irvine, CA (poster presentation).
 - *5. Ted Pham “ Charging the Quantum Capacitance of Graphene with a Single Biological Ion Channel” UC System wide Bioengineering Symposium, June 2014, Irvine, CA (poster presentation).
 - *6. Will Wang “Charging the Quantum Capacitance of Graphene with a Single Biological Ion Channel”, Biophysical Society 58th Annual Meeting, February 2014, San Francisco, CA. (poster Presentation)
 - *7. Will Wang “Charging the Quantum Capacitance of Graphene with a Single Biological Ion Channel”, MRS Spring meeting 2014, April 2014, San Francisco, CA.
 - *8. Katayoun Zand “Nanochannel Trap Arrays For Monitoring Single Mitochondrion Behavior”, Biophysical Society 58th Annual Meeting, February 2014, San Francisco, CA.
 - *9. Katayoun Zand “Nanochannel Devices for Single Mitochondrion Membrane Potential Assays” MRS Spring meeting 2014, April 2014, San Francisco, CA.
 - *10. Katayoun Zand “ Nanochannel Trap Arrays For Monitoring Single Mitochondrion Behavior” UC Systemwide Bioengineering Symposium, June 2014, Irvine, CA
11. Peter Burke “THz Wireless Communication”, IEEE Radio and Wireless Symposium, January 21, 2014, Newport Beach, CA
12. Peter Burke “Nanochannel Trap Arrays for Monitoring Single Mitochondrion Behavior”, NCI-NIBIB Point of Care Technologies for Cancer Conference, January 8-10, 2014, Bethesda, Maryland.
13. Peter Burke “Nanofluidic Platform for Single Mitochondria Analysis Using Fluorescence Microscopy”, 21th ECDO Euroconference on Apoptosis, September 25-28, 2013, Paris, France.

Since last review
(2/2013)

Conference Presentations under #W911NF-11-1-0024

- *14. Peter Burke “Protein nanopore-gated bio-transistor for membrane ionic current recording” Transport through Nanopores: From Understanding to Engineering, August 1, 2013, Bremen, Germany.
- *15. Peter Burke “Nanofluidic Based Assays of Mitochondria”, Summit 2013, March 25-26,2013, Irvine, CA.
- *16. Peter Burke “Supported Lipid Bilayer Nanopore Protein Gated All Semiconducting Nanotube Network Devices”, Biophysical Society 57th Annual Meeting, February 2-6, 2013, Philadelphia, PA.
- *17. Katayoun Zand, Ted Pham, Antonio Davila Jr, Douglas C. Wallace, Peter Burke. “Novel Approach Towards Trapping and Imaging of Individual Mitochondria”, MMB 2013 Technical Digest, April 2013.
- 18. Peter Burke. “Radio Frequency Nanoelectronics Based on Carbon Nanotubes”, 80th Automatic RF Techniques Group (ARFTG) Conference, November 30, 2012, San Diego, CA
- 19. Peter Burke “Nano-electromagnetics in 1d systems”, International Symposium on Electromagnetic Compatibility (EMC Europe), September 21, 2012, Rome, Italy
- 20. Peter Burke “Nanoelectrode and Nanofluidic Based Assays of Ion Channels, Mitochondria Membrane Potential, and Apoptosis”, 3rd International LifeChips Symposium, February 9, 2012, Irvine, CA
- 21. Peter Burke. “Radio Frequency Nanoelectronics Based on Carbon Nanotubes”, SiRF 2012, January 2012, Santa Clara, CA
- 22. Peter Burke. “Fabrication of Supported Lipid Bilayer (SLB) and Nanotube Hybrid Transistor Biosensing Platform Using Microfluidic Channels”, Micro TAS 2011, October 5, 2011, Seattle, WA
- 23. Peter Burke. “Effect of Source, Surfactant, Deposition Process on Electronic Properties of Nanotube Arrays”, FACSS, Reno, NV, October 4, 2011.
- 24. Peter Burke. “Sheet Resistance of Multi-Layer Graphene in Radio Frequency”, Nano-DDS 2011, August 2011, Brooklyn, NY.
- 25. Peter Burke. “Broadband Conductivity of Graphene from DC to THz”, IEEE NANO 2011, August 2011, Portland, OR
- 26. Peter Burke. “All-Semiconducting Nanotube Networks: Towards High Performance Printed Nanoelectronics” *University of Lille & Institute d’Electronique Micro et Nanotechnologie*, March 2011, Lille, France.
- 27. Dheeraj Jain “All-Semiconducting nanotube networks Thin Film Transistors: An Insight Towards High Performance Printed Nanoelectronics”, APS March meeting, March 2011, Dallas, TX.

HSAP add-on

Student Name	Grade Level	School	Project
Anna Resnick	High School Junior	Whitney High School	Graphene Characterization
Jenny Lee	College Sophomore	UCI	Cell culture



*NanoEngineering
Research Lab*

*University of Illinois
at Chicago
College of Engineering*

Applications to Near and Far-Field Interfaces to DNA-Guided Nanostructures --- Nanoscale Graphene-based and DNA Nanostructures and Phonon Interactions in Si Photonics: DNA+graphene+aptamers

Michael A. Stroscio^{a,b,c}

August 2014

UIC MURI Contribution under Prof. Peter Burke

^aElectrical and Computer Engineering Department, U. of Illinois at Chicago (UIC)

^bPhysics Department, U. of Illinois at Chicago

^cBioengineering Department, U. of Illinois at Chicago



*NanoEngineering
Research Lab*

*University of Illinois
at Chicago
College of Engineering*

Topics

Events and New Publications and Talks

DNA-based aptamer sensor on graphene underlying CNTs on origami
(with Marshall U, UCI, ARL)

Functionalizing graphene and origami with aptamers (with Marshall U, UCI, ARL)

Phonon Interactions in Si Photonics (with U Penn)

Events and New Publications and Talks

- Interactions with UCI, Marshall U. and U. Penn; **visit to U Penn planned in Sep 8-10, 2014 period**
- Ke Xu, Mohsen Puraamad, Kimber Brenneman, Xenia Meshik, Sidra Farid, Shripriya Poduri, Preeti Pratap, Justin Abell, Yiping Zhao, Barbara Nichols, Eugene Zakar, Michael Stroschio, and Mitra Dutta, Design and Applications of Nanomaterial-Based and Biomolecule-Based Nanodevices and Nanosensors, Chapter 3 in Design and Applications of Nanomaterials for Sensors, Jorge M. Seminario, Editor, pages 61-98, Challenges and Advances in Computational Chemistry and Physics 16, Series Editor J. Leszczynski, Springer (2014). ISBN 978-94-017-8847-2 DOI: 10.1007/978-94-017-8848-9 **With ARL**
- Xenia Meshik, Ke Xu, Mitra Dutta, and Michael A. Stroschio, Optical Detection of Lead and Potassium Ions Using a Quantum-Dot-Based Aptamer Nanosensor, IEEE Transactions in Nanobiotechnology, 13(2):161-4, June 2014, doi: 10.1109/TNB.2014.2317315. Epub 2014 Apr 22, April, 22 2014 (epub ahead of print).
- Ke Xu, Xenia Meshik, Barbara M. Nichols, Eugene Zakar, Mitra Dutta, and Michael A. Stroschio, Graphene- and aptamer-based electrochemical biosensor, Nanotechnology, 25(20), 205501 (2014); DOI:10.1088/0957-4484/25/20/205501 **With ARL**
- Ke Xu, Xenia Meshik, Min Choi, Tsai-Chin Wu*, Michael Norton*, Mitra Dutta, and Michael A. Stroschio, Study of Electric Field Caused by Semiconductor Quantum Dots in Close Proximity to DNA Origami, International Workshop on Computational Electronics, Paris, France, July 2014. **With Marshall U.; Accompanying proceedings paper under review.**
- M.S. Choi, N. Zhang, M. Dutta, M.A. Stroschio, C.O. Aspetti and R. Agarwal, Plasmon Excitation of Coherent Interface Phonons in Si-SiO₂ Systems, International Workshop on Computational Electronics, Paris, France, Jul 2014. **With U Penn; Accompanying proceedings paper under review.**

1. Graphene Platform (Testbed II)
with ARL and UCI

2. Origami Platform (DNA Origami Team)
from Marshall U. for Beacon-Origami Studies

3. Nanophotonics (Testbed III) Collaboration with U. Penn: New Initiative for 4th-5th Yrs

New Initiative for 4th and 5th Years --- following 4th Year Review); with the recent commencement of the 4th year these initial results in identifying relevant physical phenomena will be used to formulate an inclusive model.



*NanoEngineering
Research Lab*

*University of Illinois
at Chicago
College of Engineering*

TESTBEDS



TESTBED I
SiNW



TESTBED II
Carbon



TESTBED III
Nanophotonics

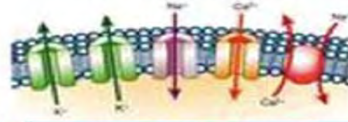
FUNCTIONALIZATION

FUNCTIONALIZATION SCHEME I



DNA Origami
Team

FUNCTIONALIZATION SCHEME II



Ion Channel
Team

CHARACTERIZATION

- SELECTIVITY
- SENSITIVITY
- SPECIFICITY

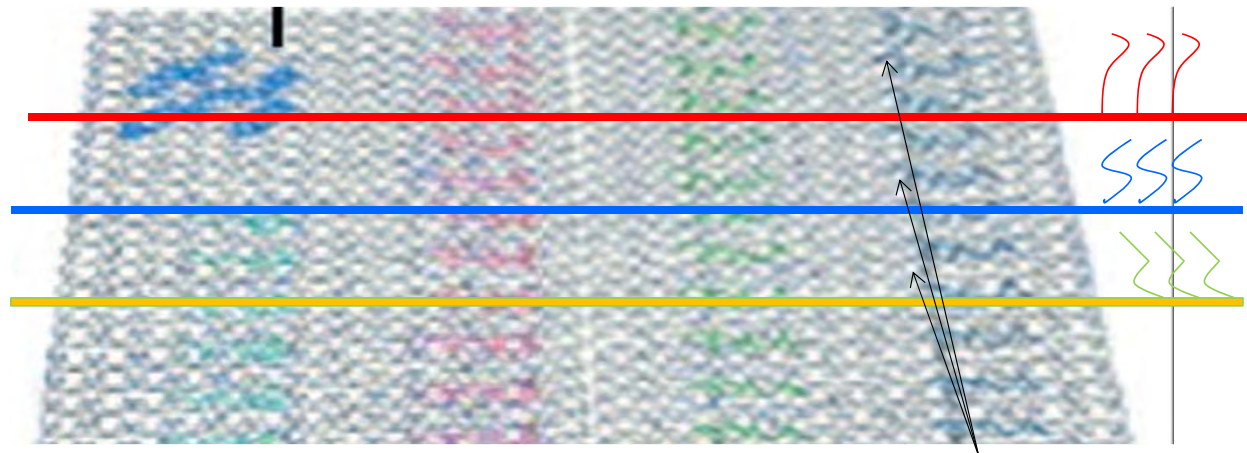
DC

THz

Photonic

Nano-optical Sensors on Origami Host

Working in multidisciplinary field incorporating nanoelectronics, nano-optoelectronics, molecular switches, DNA structures and aptamers, selective-binding of biomolecules to inorganic materials, and transitions between DNA (HOMO & LUMO states) to crystalline (E_c and E_v) states.

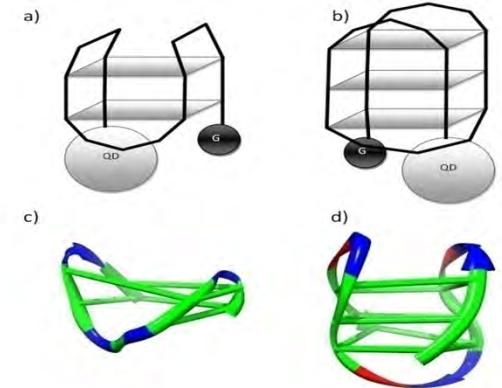


Background origami illustration from Bhatia et al. *Current Opinion in Biotechnology* 2011, 22,47 C484

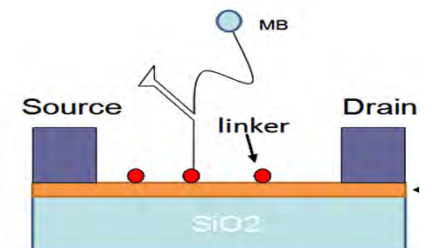
Aptamers on CNTs
on Origami

Key Design Concept: Multiple CNTs, Different Aptamers,
Multiplexed Nanosensing

Either Electrical or Optical Output



Example of
Optical Signal



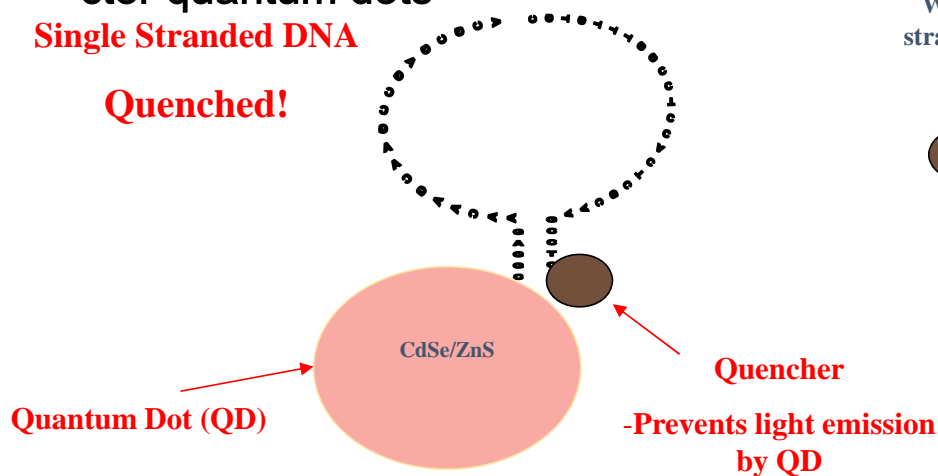
Example of
Electrical Signal

Nanoprobes for Molecule/Ion Detection

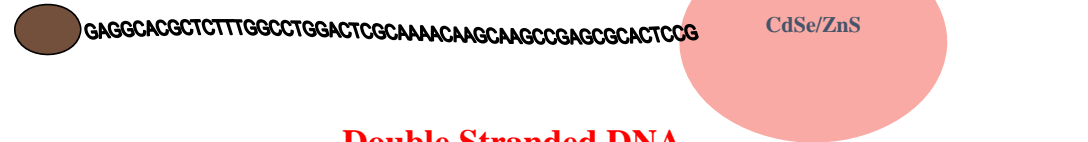
Conventional beacon -- design molecular beacons (MBs) using DNA and nanoscale semiconductor quantum dots

Single Stranded DNA

Quenched!



When the complementary DNA strand is introduced the double stranded molecule forms and the stiff QD and quencher separate – allowing the QD to emit light



Double Stranded DNA

QD quenched

QD emits light!

OPTICAL OUTPUT

Unconventional beacon – replaces single –stranded DNA with a DNA *aptamer* that exhibits analyte binding specificity

Using binding-selective DNA molecules, known as aptamers, nanoscale quantum-dot-based sensors for detecting analytes can be fabricated as **aptamer-based molecular beacons**; these aptamer-based molecular beacons can potentially be used in multiple-analyte scenarios.

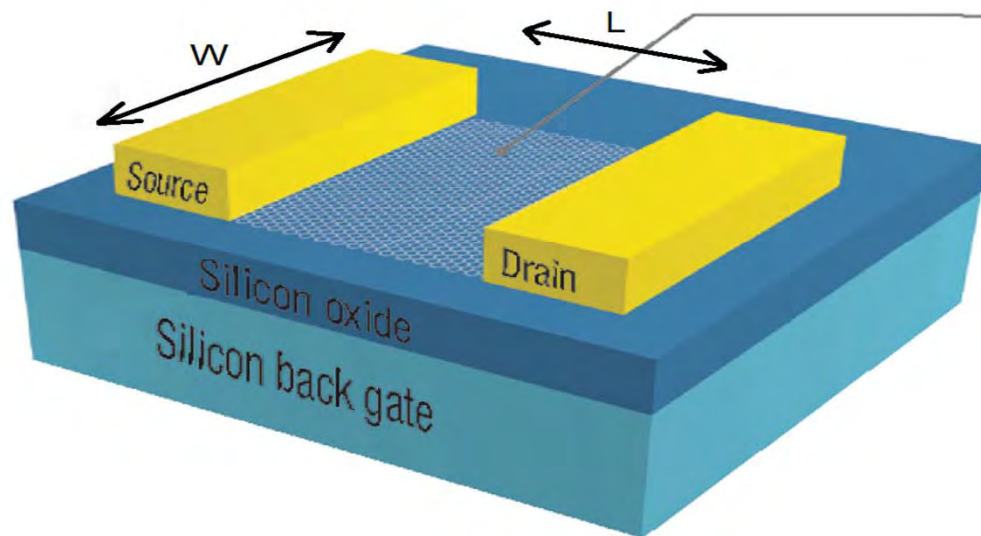
THRUST: MAKE FUNCTIONAL ON ORIGAMI SCAFFOLD

Collaboration with UCI, Marshall U, and ARL
– Graphene-based DNA-aptamer based
Nanosensors

Aptamer-based Detector

*Graphene used to test
concepts for nanosensors
underlying origami-CNT structures*

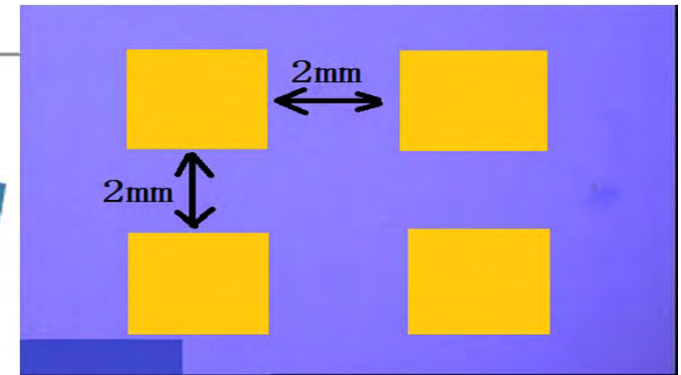
Collaboration with ARL



ARL Sample ID: LPC036B1TC

•Raman data indicates graphene films are 6% single layer,
94% bilayer graphene

Data taken from a 40 x 60 mm area in the middle of the sample
—(~ 10 mm left and 7 mm down of the upper right hand corner)



Yellow rectangle are metal contacts
(Source and Drain)

HP 4156B/C semiconductor
parameter analyzer

- Source and Drain contacts are made of Cr/Au (5 nm/50 nm).
- Length (L) and width (W) of channel is both 2 mm. Four identical channels are made in this wafer.
- Thickness of SiO₂ is 2960 Å
- Degenerately doped Si (thickness = 525 μm, resistivity = 0.005 Ω -cm) is used as the back gate. In order to have good measurements, copper wire is attached to the gate. I_{sd} vs V_{sd} is tested. FET characteristic tested shows clear gate voltage control over source-drain current. Ambipolar electric field effect observed.

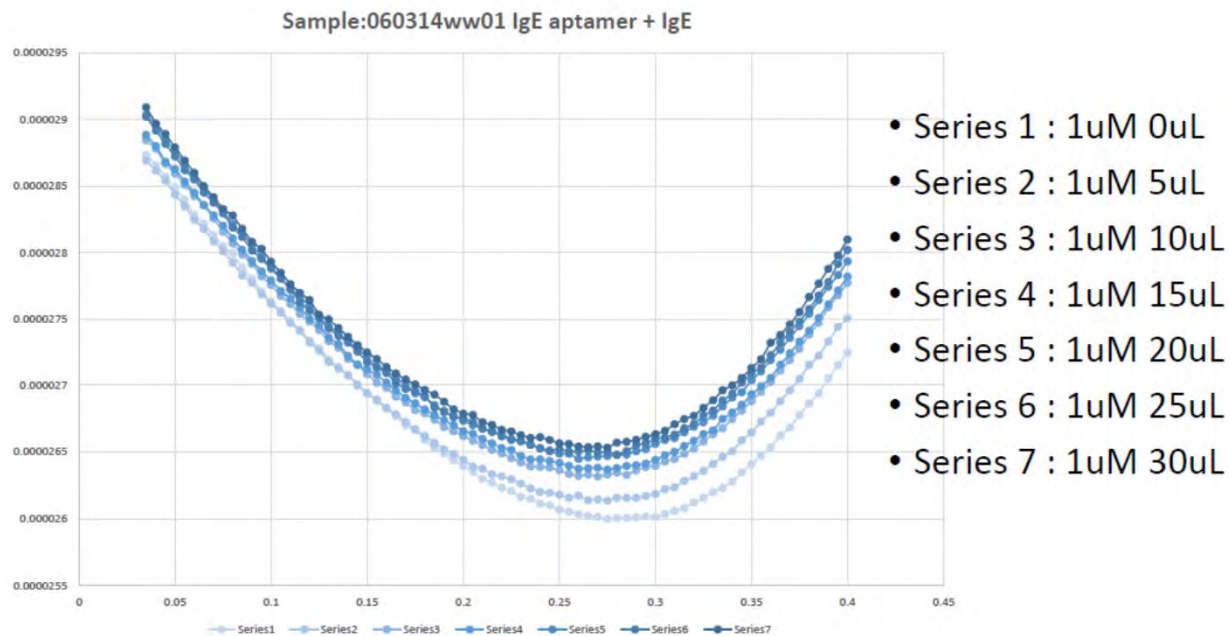
Graphene-based DNA-aptamer-based Nanosensors

Past UIC DNA aptamer-based detection efforts: K, Pb, Zn, cocaine – small molecules and ions Many past efforts have used ARL-produced graphene layers for aptamer detectors

The latest graphene-based sensor platforms from UCI (Burke) have been received at UIC in Spring 2014 and have been used in Summer 2014 to extend aptamer-based nanobiosensor research ---- Example here covers newly-obtained (Jun 2014) data on I-V curves for aptamer-based IgE detection on graphene substrate



UCI Graphene based Nanosensor Platform

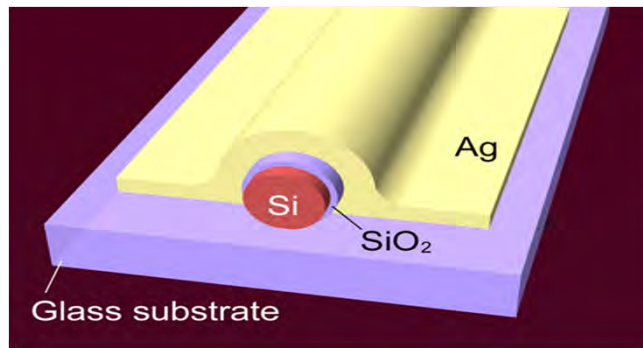


Nanophotonics (Testbed III) Collaboration with **U. Penn:** New Initiative for 4th-5th Yrs

New Initiative for 4th and 5th Years --- following 4th Year Review); with the recent commencement of the 4th year these initial results in identifying relevant physical phenomena will be used to formulate an inclusive model

Surface-Plasmon Coupled Silicon

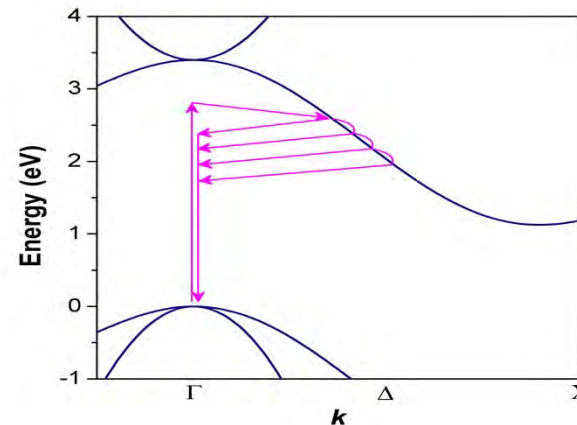
The challenge as defined by U. Penn (U. Penn figures below – from February 2014 MURI Review):



Ω -Cavity

Cho, C.-H.; Aspetti, C. O.; Park, J.; Agarwal, R.
Nature Photonics (2013)

Collaboration with U Penn – PL from Si



Collaboration with U Penn – PL from Si

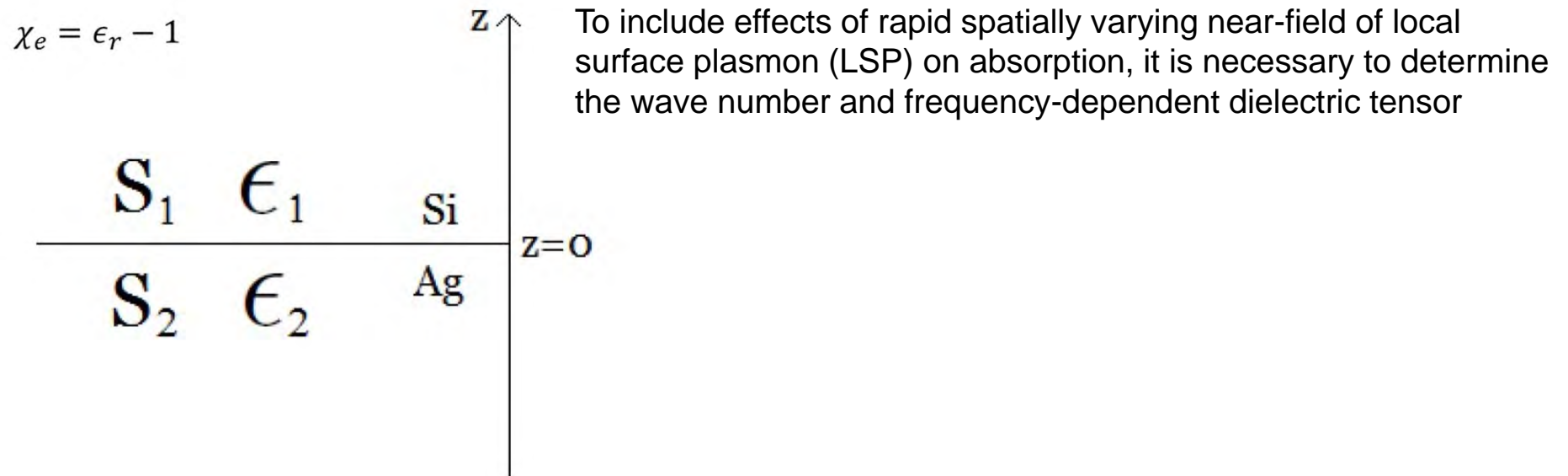


Fig. 1: Si-Ag heterostructure

EM Fields near Ag-Si interface: z-axis is perpendicular to interface

$$\left. \begin{aligned} H_y(z) &= A_1 e^{i\beta x} e^{-s_1 z} \\ E_x(z) &= iA_1 \frac{1}{\omega \epsilon_1 \epsilon_0} s_1 e^{i\beta x} e^{-s_1 z} \\ E_z(z) &= -A_1 \frac{\beta}{\omega \epsilon_1 \epsilon_0} e^{i\beta x} e^{-s_1 z} \end{aligned} \right\} z > 0$$

$$\left. \begin{aligned} H_y(z) &= A_2 e^{i\beta x} e^{s_2 z} \\ E_x(z) &= -iA_2 \frac{1}{\omega \epsilon_2 \epsilon_0} s_2 e^{i\beta x} e^{s_2 z} \\ E_z(z) &= -A_2 \frac{\beta}{\omega \epsilon_2 \epsilon_0} e^{i\beta x} e^{s_2 z} \end{aligned} \right\} z < 0,$$

$$s_i = s_{z,i} \quad (i = 1, 2)$$

$$A_1 = A_2$$

$$\frac{s_2}{s_1} = -\frac{\epsilon_2}{\epsilon_1},$$

$$s_i^2 = \beta^2 - k_0^2 \epsilon_i \quad (i = 1, 2)$$

$$e_x = \begin{cases} -\frac{is_2}{\omega \epsilon_2 \epsilon_0} e^{s_2 z} & z < 0 \\ \frac{is_1}{\omega \epsilon_1 \epsilon_0} e^{-s_1 z} & z > 0 \end{cases}$$

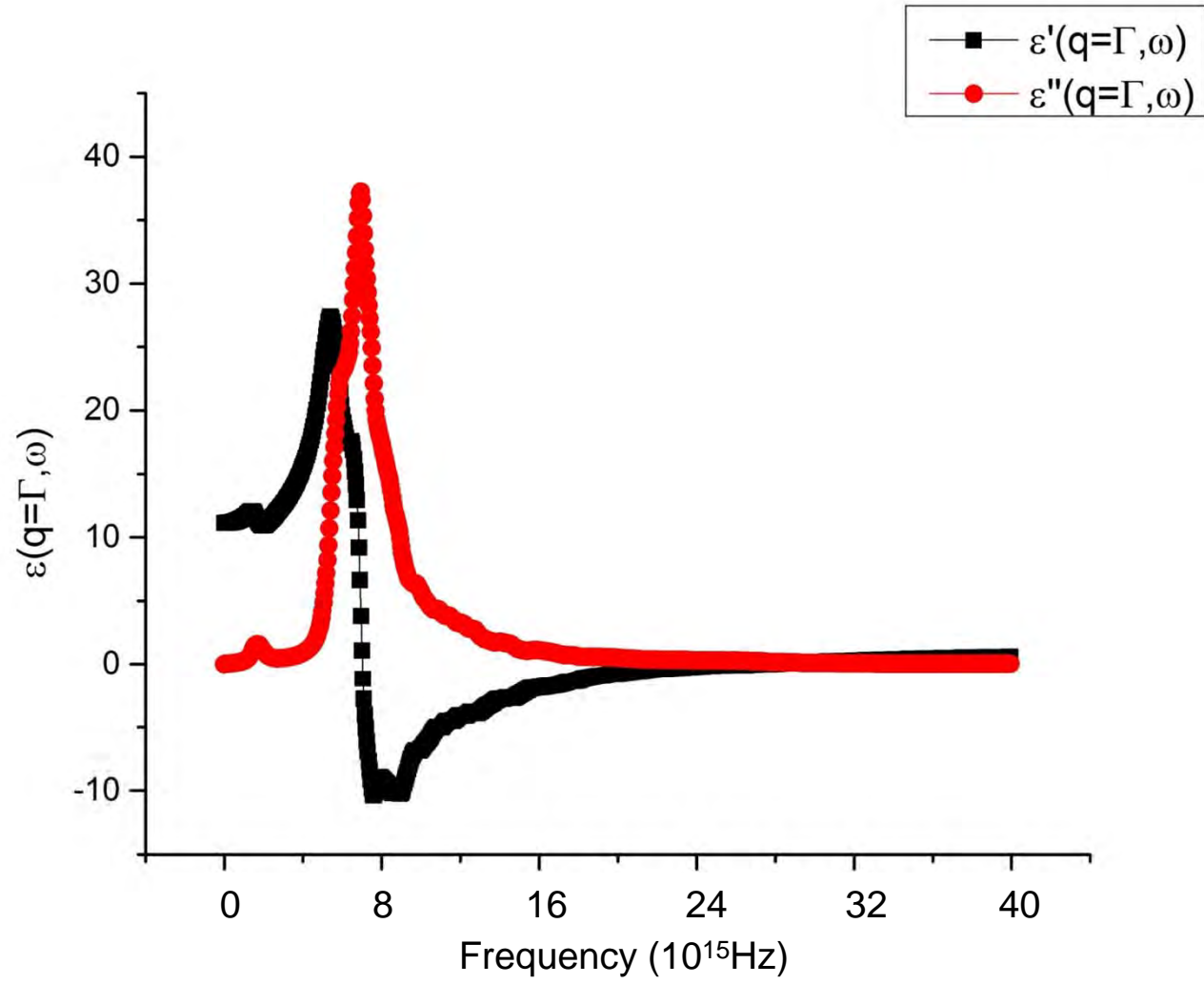
$$e_z = \begin{cases} -\frac{\beta}{\omega \epsilon_2 \epsilon_0} e^{s_2 z} & z < 0 \\ -\frac{\beta}{\omega \epsilon_1 \epsilon_0} e^{-s_1 z} & z > 0 \end{cases}$$

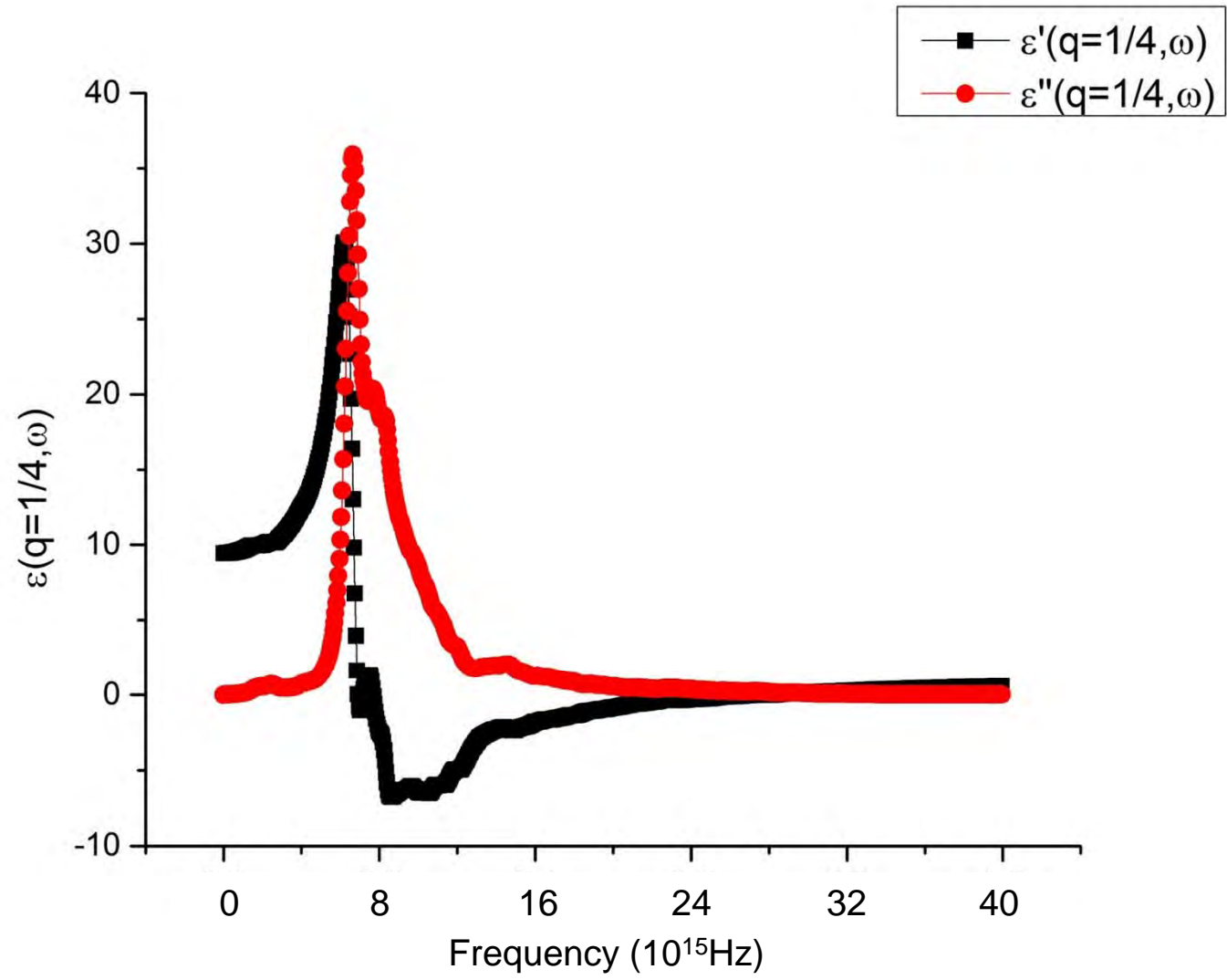
TDDFT (Time Dependent Density Functional Theory) Simulation – ELK (electrons in k-space) - an all-electron full-potential linearized augmented-plane wave (FP-LAPW) code with many advanced features ----- <http://elk.sourceforge.net/>

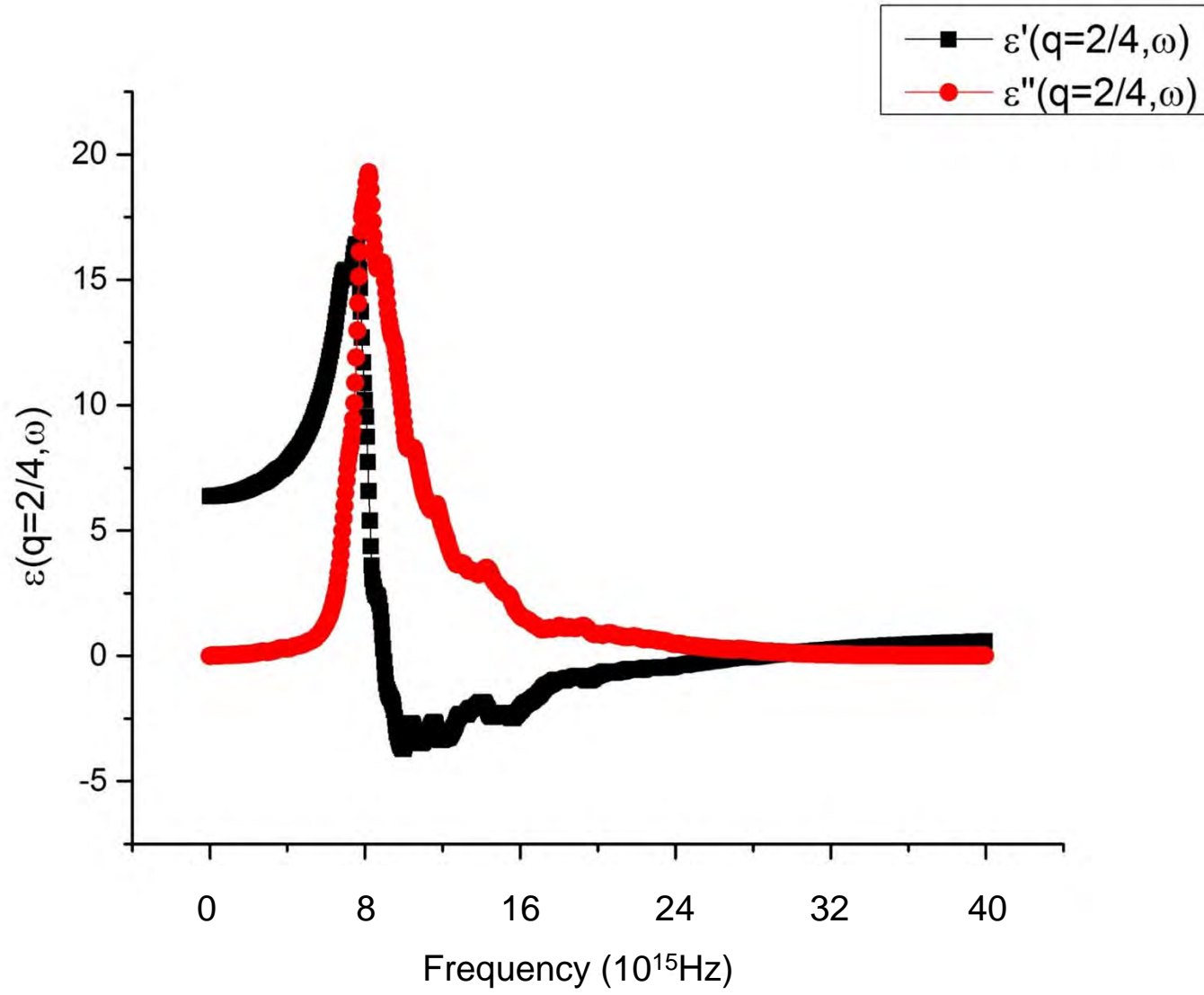
- Random Phase Approximation
- 137 plane wave basis sets
- 9 bands
- From Γ point (0,0,0) to X point $\frac{2\pi}{a} \left(0, \frac{1}{2}, \frac{1}{2}\right)$

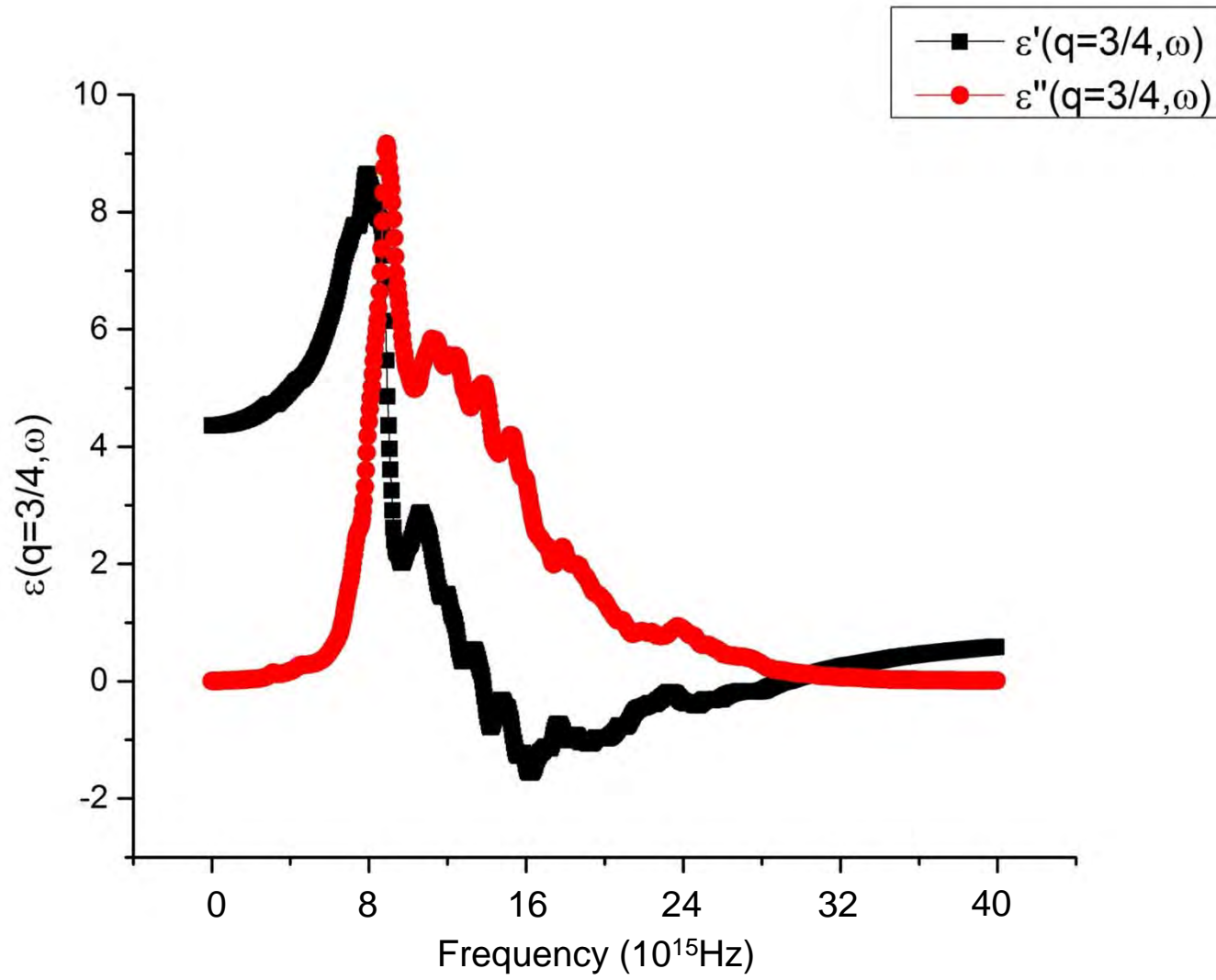
$$P_{abs}^{(NL)} \approx \frac{\omega \epsilon_0 |E_0^x|^2}{4\pi \beta''} \int \frac{\chi''_{xx}(\vec{q}, \omega)}{|s_1 + iq_z|^2} dq_z.$$

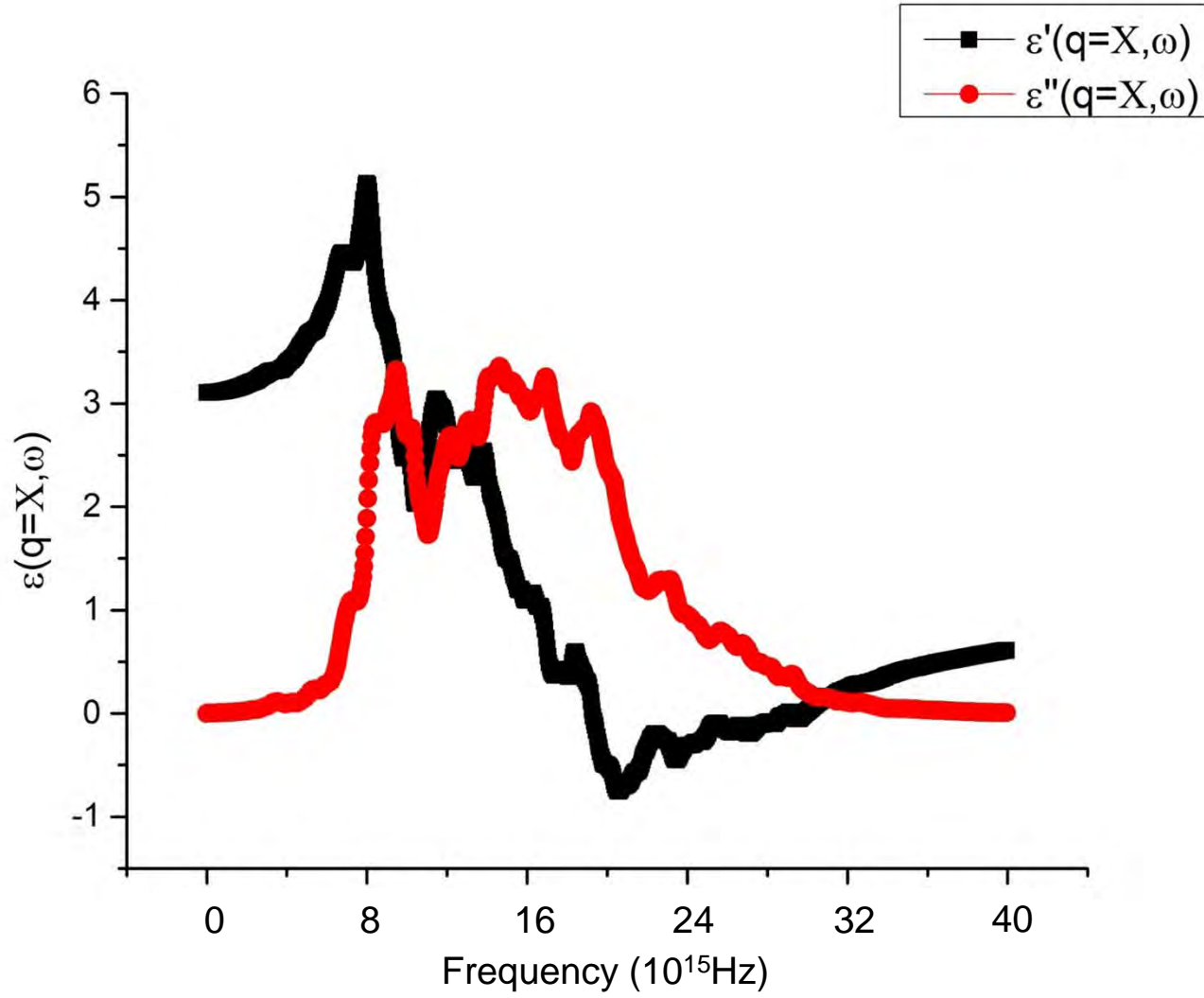
Include effects of rapid spatially varying near-field of LSP (local surface plasmon) on absorption, it is necessary to determine the wave number and frequency-dependent dielectric tensor (Jung et al. 2011)

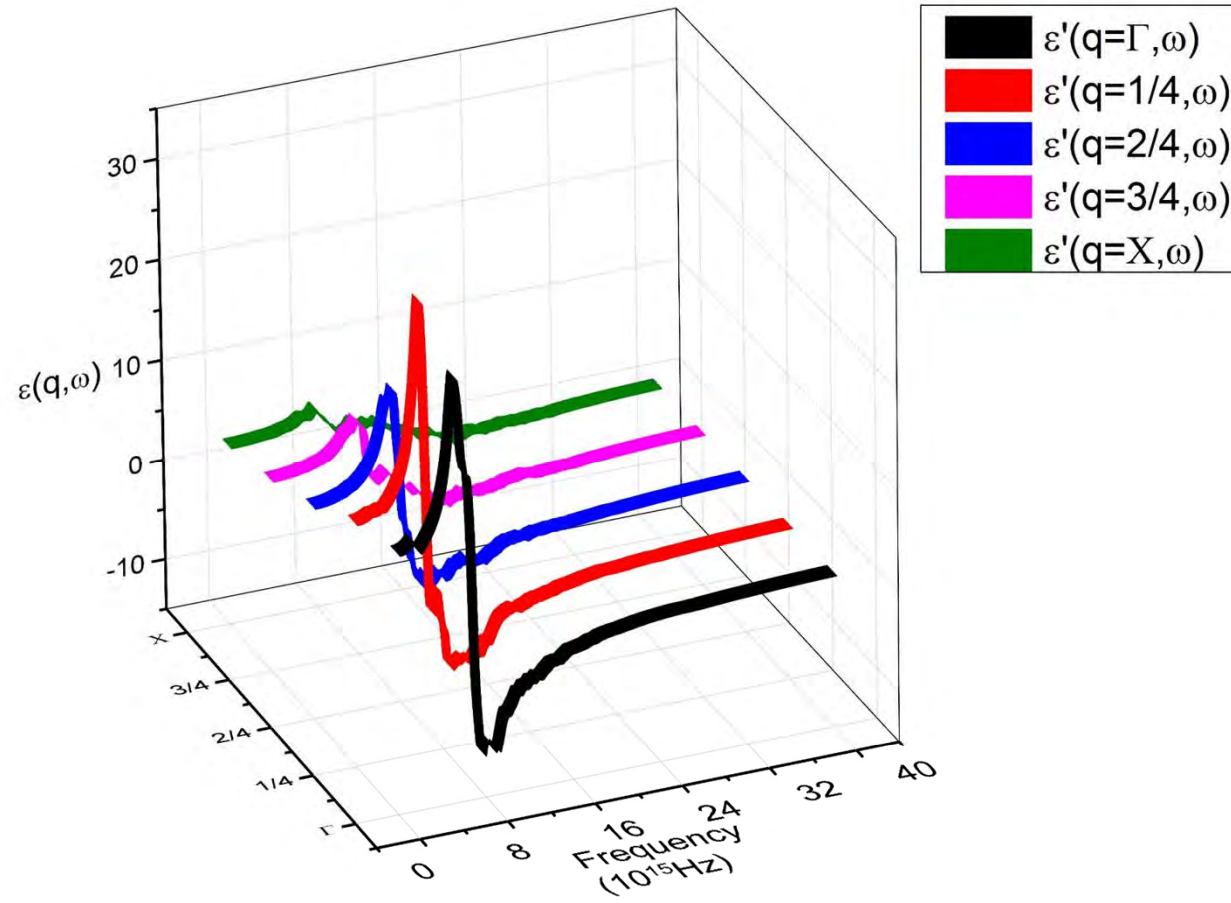


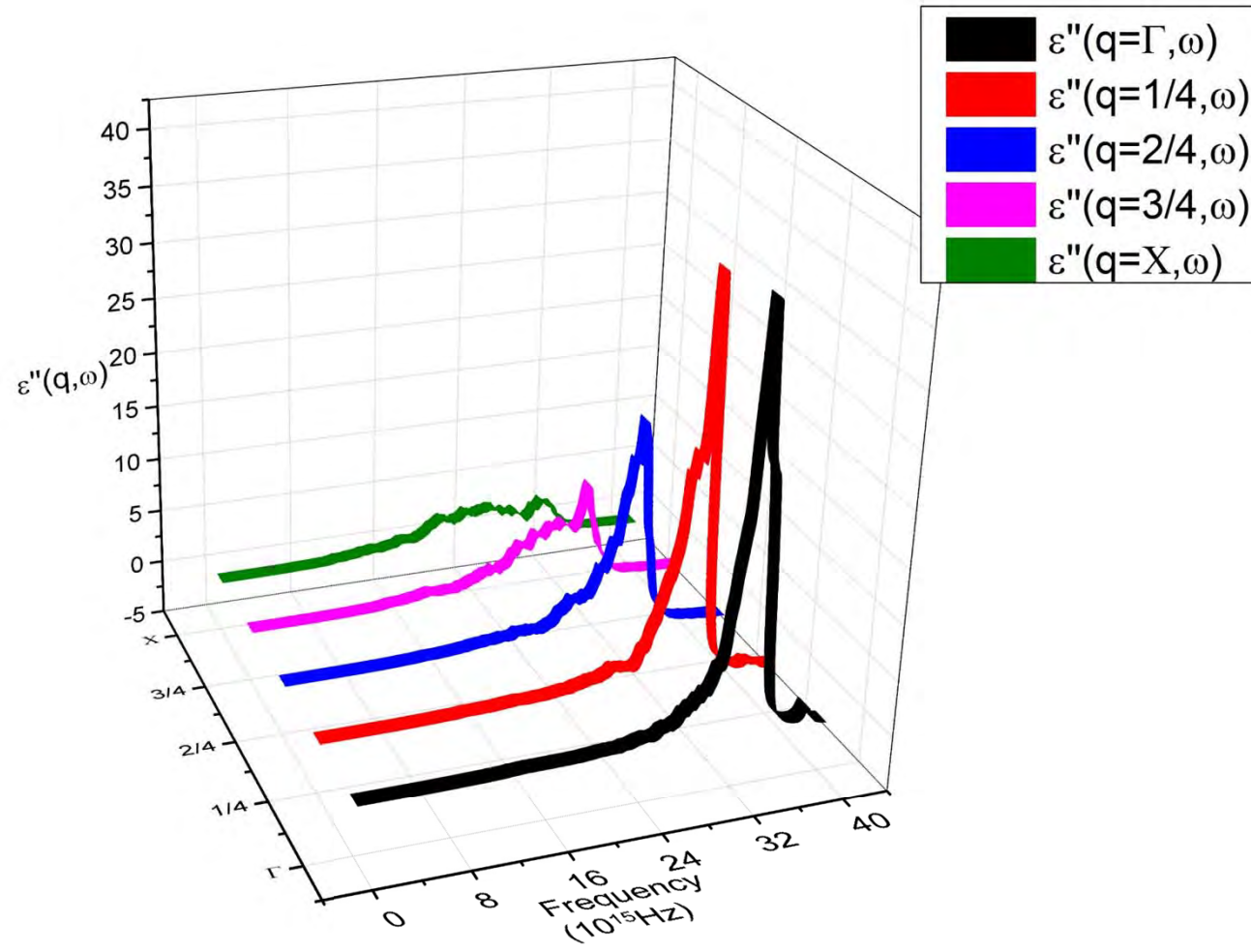


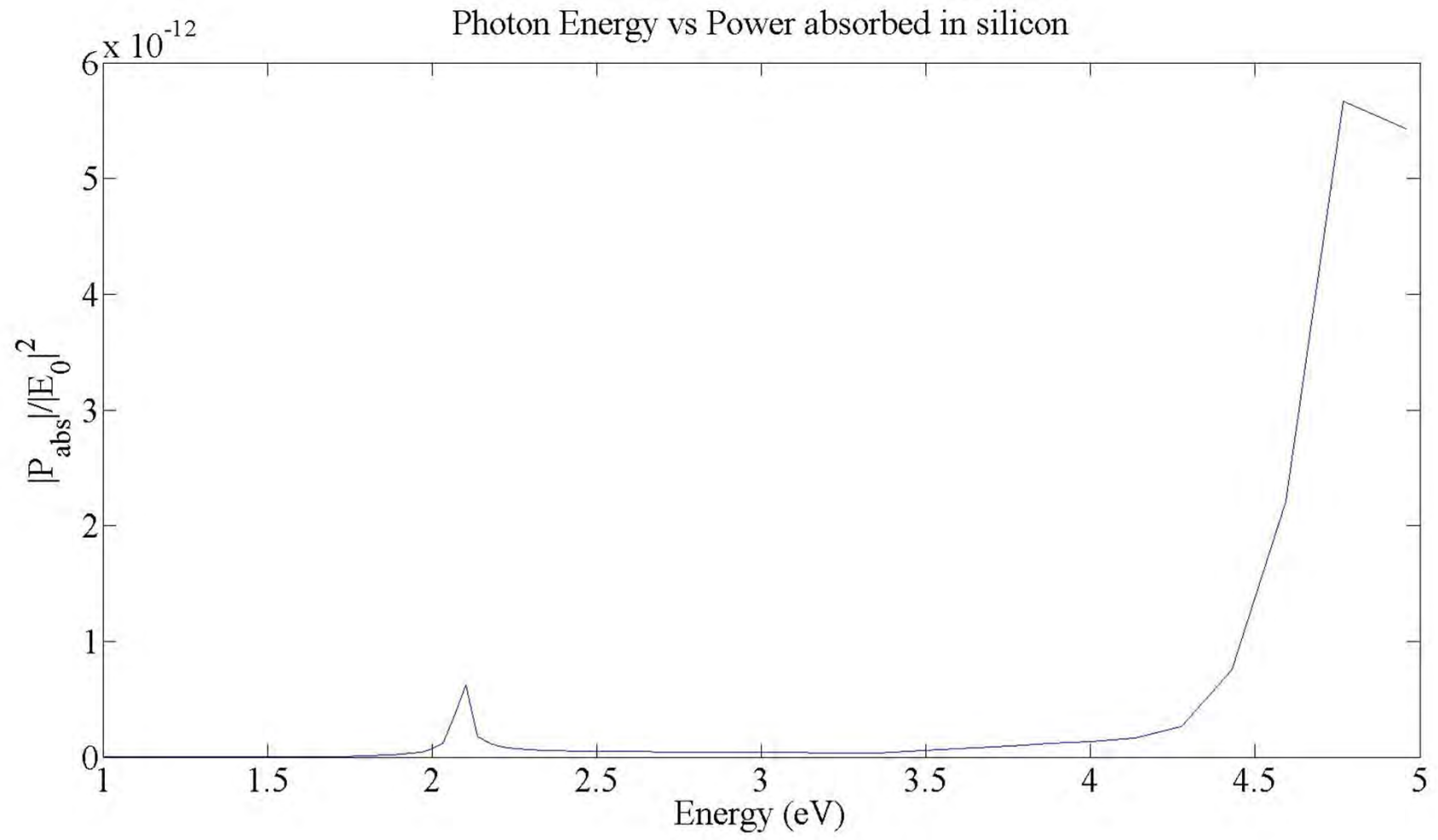










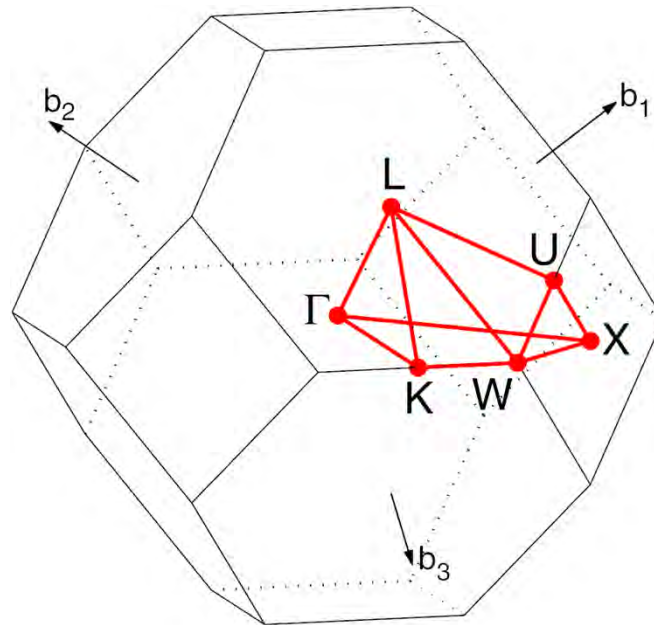


Parameter	Value	Reference
E_0	1	
χ_ω^*	0.25×10^{-18}	D. Dimitropoulos, et al. "Phase-matching and Nonlinear Optical Processes in Silicon Waveguides." Optics Express Vol. 12, Issue 1, pp. 149-160 (2004)
β	$k_0 \sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}}$	S. Maier. Plasmonics: Fundamentals and Applications. New York: Springer, 2007
s_1	$-\sqrt{\beta^2 - \epsilon_1 k_0^2}$	$s_1 < 0$ for a bound state solution
ϵ_1 (silicon)	Experimental	Green, "Self-consistent optical parameters of intrinsic silicon at 300 K including temperature coefficients" silicon property Solar Energy Materials & Solar Cells 92 (2008) 1305-1310
ϵ_2 (silver)	$\epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$	

* Dimitropoulos

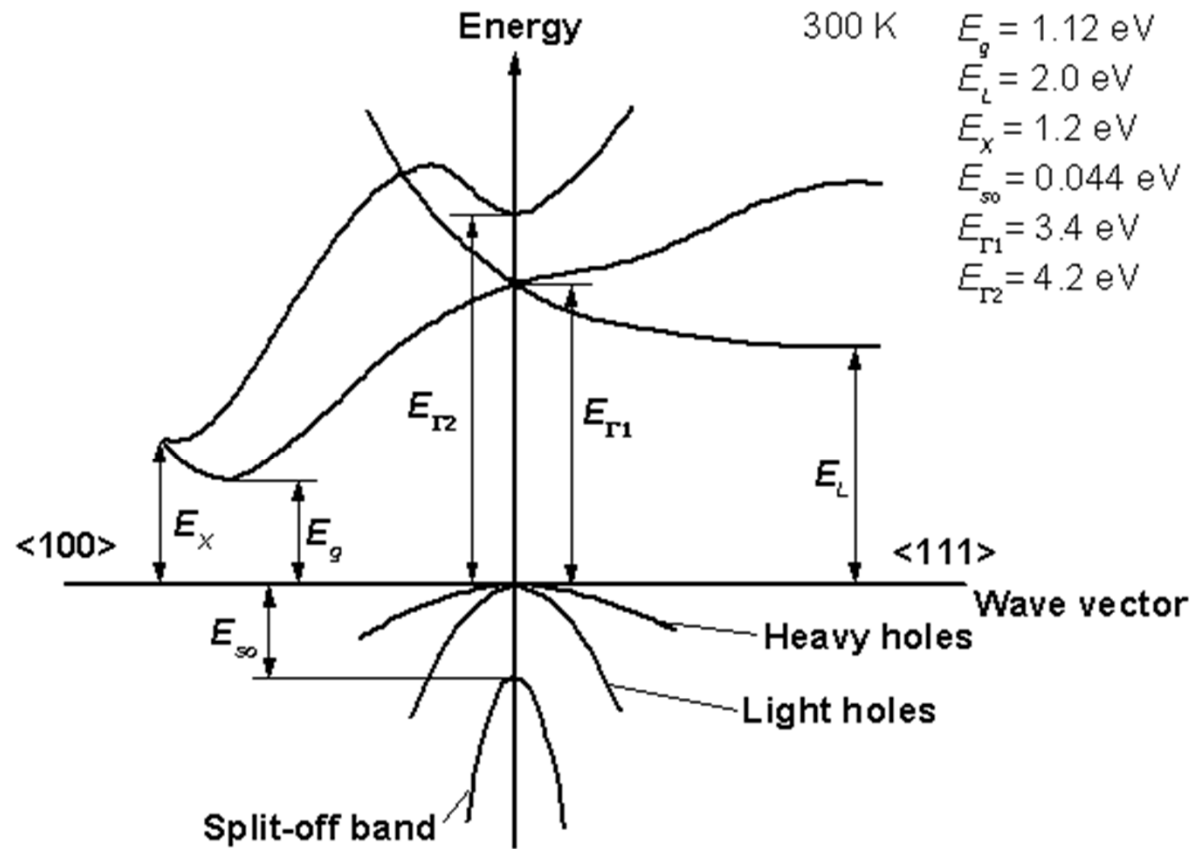
Backup

FCC Brillouin zone lattice vectors



FCC path: Γ -X-W-K- Γ -L-U-W-L-K|U-X

[Setyawan & Curtarolo, DOI: 10.1016/j.commatsci.2010.05.010]



Real space lattice vectors

$$\begin{aligned}
 \mathbf{X} &= \begin{pmatrix} 0 & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \cdot \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \\ \vec{b}_3 \end{pmatrix} = \frac{2\pi}{a} (1 \ 0 \ 0); & \mathbf{U} &= \begin{pmatrix} 0 & \frac{5}{8} & \frac{3}{8} \end{pmatrix} \cdot \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \\ \vec{b}_3 \end{pmatrix} = \frac{2\pi}{a} \begin{pmatrix} 1 & -\frac{1}{4} & \frac{1}{4} \end{pmatrix}; \\
 \mathbf{L} &= \begin{pmatrix} 0 & \frac{1}{2} & 0 \end{pmatrix} \cdot \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \\ \vec{b}_3 \end{pmatrix} = \frac{2\pi}{a} \begin{pmatrix} \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}; & \mathbf{W} &= \begin{pmatrix} \frac{1}{4} & \frac{3}{4} & \frac{1}{2} \end{pmatrix} \cdot \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \\ \vec{b}_3 \end{pmatrix} = \frac{2\pi}{a} \begin{pmatrix} 1 & 0 & \frac{1}{2} \end{pmatrix}; \\
 \mathbf{K} &= \begin{pmatrix} \frac{3}{8} & \frac{3}{4} & \frac{3}{8} \end{pmatrix} \cdot \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \\ \vec{b}_3 \end{pmatrix} = \frac{2\pi}{a} \begin{pmatrix} \frac{3}{4} & 0 & \frac{3}{4} \end{pmatrix}
 \end{aligned}$$

K-space lattice vectors

Symmetry points (u, v, w)	$[k_x, k_y, k_z]$	Point group
$\Gamma: (0, 0, 0)$	$[0, 0, 0]$	m3m
X: $(0, 1/2, 1/2)$	$[0, 2\pi/a, 0]$	4/mmm
L: $(1/2, 1/2, 1/2)$	$[\pi/a, \pi/a, \pi/a]$	3m
W: $(1/4, 3/4, 1/2)$	$[\pi/a, 2\pi/a, 0]$	42m
U: $(1/4, 5/8, 5/8)$	$[\pi/2a, 2\pi/a, \pi/2a]$	mm2
K: $(3/8, 3/4, 3/8)$	$[3\pi/2a, 3\pi/2a, 0]$	mm2

$$P_{abs}^{(Ag)} = \frac{\omega \epsilon_0 \epsilon_2''}{4\beta''} \int_0^h (|E_x|^2 + |E_z|^2) dz \Delta y$$

$$|e_x|^2 = \begin{cases} \left| \frac{s_2}{\omega \epsilon_2 \epsilon_0} \right|^2 e^{2s_2 z}, z < 0 \\ \left| \frac{s_1}{\omega \epsilon_1 \epsilon_0} \right|^2 e^{-2s_1 z}, z > 0 \end{cases}$$

$$|e_z|^2 = \begin{cases} \left| \frac{\beta}{\omega \epsilon_2 \epsilon_0} \right|^2 e^{2s_2 z}, z < 0 \\ \left| \frac{\beta}{\omega \epsilon_1 \epsilon_0} \right|^2 e^{-2s_1 z}, z > 0 \end{cases}$$

$$P_{abs}^{(Ag)} = \frac{\omega \epsilon_0 \epsilon_2''}{4\beta''} \left[\frac{1}{2s_2} \left| \frac{1}{\omega \epsilon_2 \epsilon_0} \right|^2 \{ (|s_2|^2 + |\beta|^2)(1 - e^{-2s_2 h}) \} \right] \Delta y$$

$$P_{abs}(\omega) = \frac{\omega}{2} \text{Im} \left[\int \vec{P}_\omega(\mathbf{r}) \cdot \vec{E}_\omega(\mathbf{r})^* d^3r \right]$$

$$\vec{P}_\omega = \epsilon_0 \tilde{\chi}_\omega \vec{E}_\omega$$

$$\begin{aligned} P_{abs}^{(Si)} &= \frac{\omega |E_0|^2 \epsilon_0}{2} \text{Im} \left[\int \tilde{\chi}_\omega \left(\vec{E}_\omega(\mathbf{r}) \cdot \vec{E}_\omega(\mathbf{r})^* \right) d^3r \right] \\ &= \frac{\omega |E_0|^2 \epsilon_0}{2} \text{Im} \left[\int \tilde{\chi}_\omega (|e_x|^2 + |e_z|^2) d^3r \right] \\ &= \frac{\omega |E_0|^2 \epsilon_0 \Omega^{1/3} dx}{2} \text{Im} \left[\int \tilde{\chi}_\omega (|e_x|^2 + |e_z|^2) dz \right] \end{aligned}$$

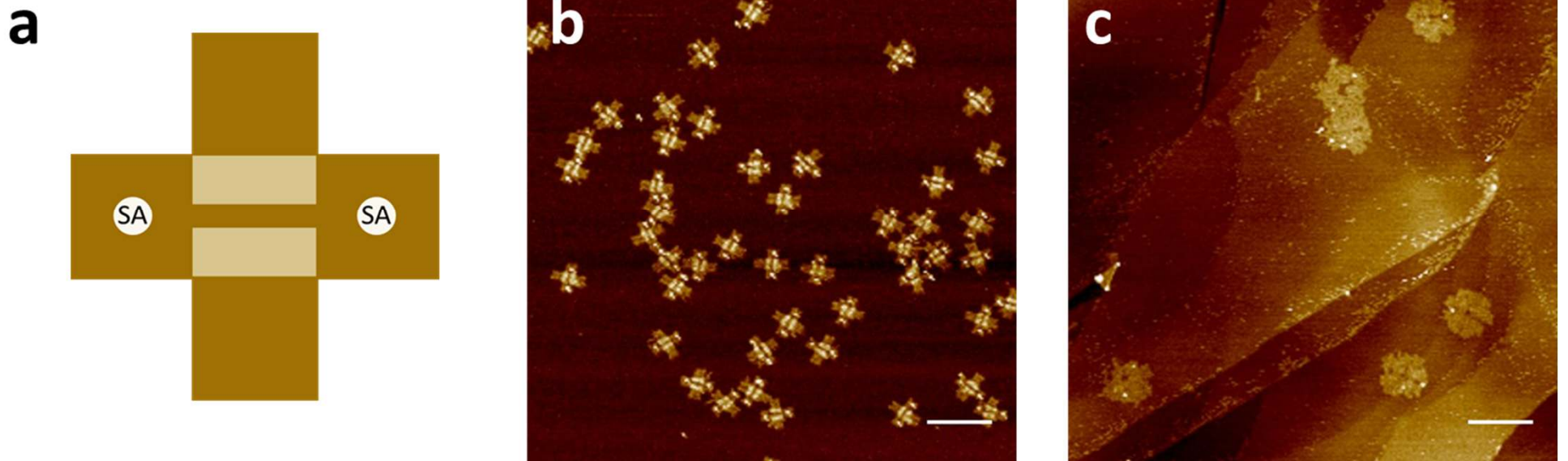
$$P_{abs}^{(Si)} = -\frac{|E_0|^2 \tilde{\chi}_\omega'' \Omega^{1/3} dx}{4\omega \epsilon_0} \left[\left| \frac{s_1}{\epsilon_1} \right|^2 + \left| \frac{\beta}{\epsilon_1} \right|^2 \right] e^{-2s_1 z}$$

MURI All Hands Meeting

Norton Lab

Nathan Green, David Neff, Michael Norton

DNA origami deposited on bulk graphite



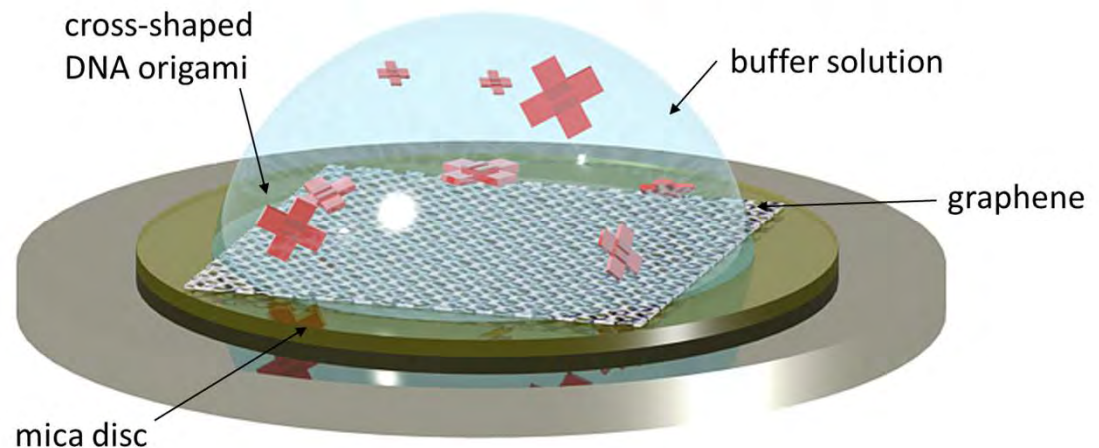
a) schematic representation of cross-shaped origami with streptavidin (SA) protein bound to each arm via biotinylated staples; b) filtered SA-complexed origami on mica; c) filtered SA-complexed origami on HOPG. Note that SA protein can still be seen attached to origami (white dots). Scale bars, 200 nm (AFM lateral); 10 nm (height scale).

DNA origami on graphene-mica substrate

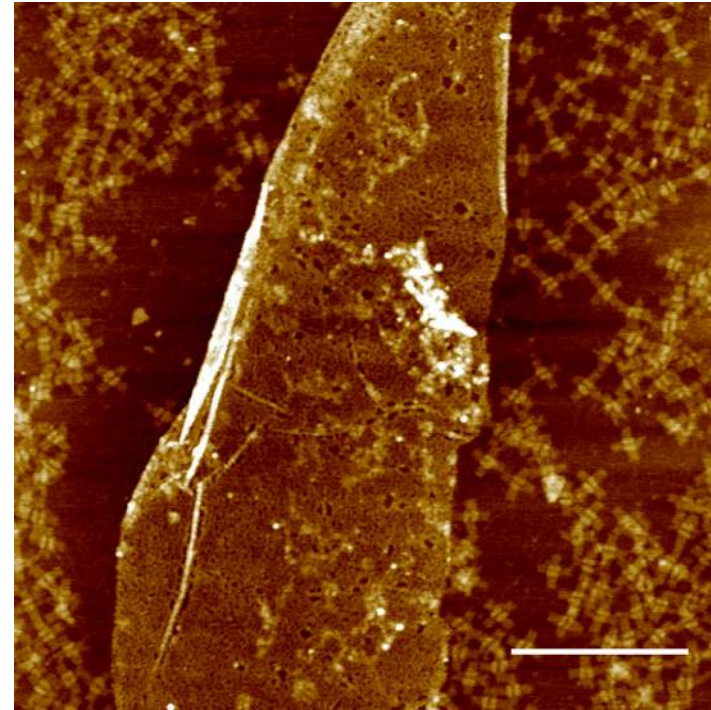
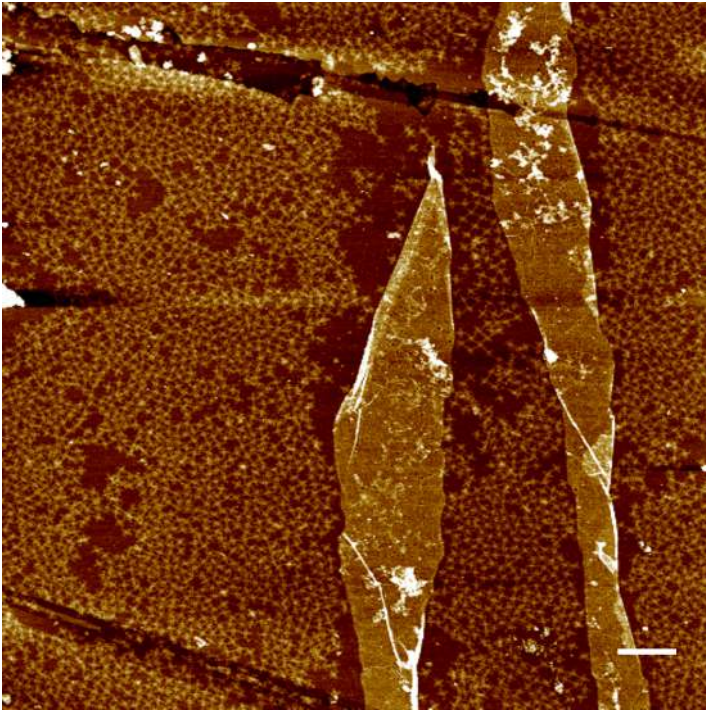
- CVD graphene transferred to mica disc by Burke group



- DNA origami prepared and deposited on graphene-mica substrate by Norton group



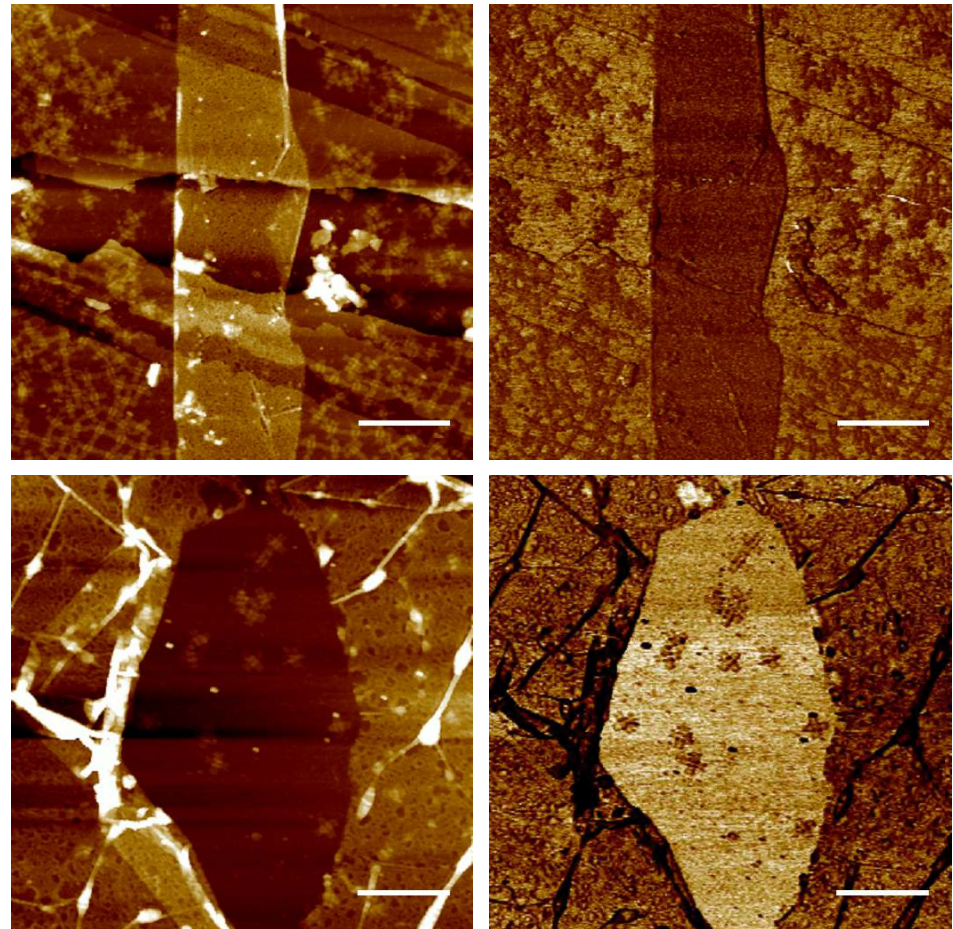
DNA origami deposited on graphene-mica



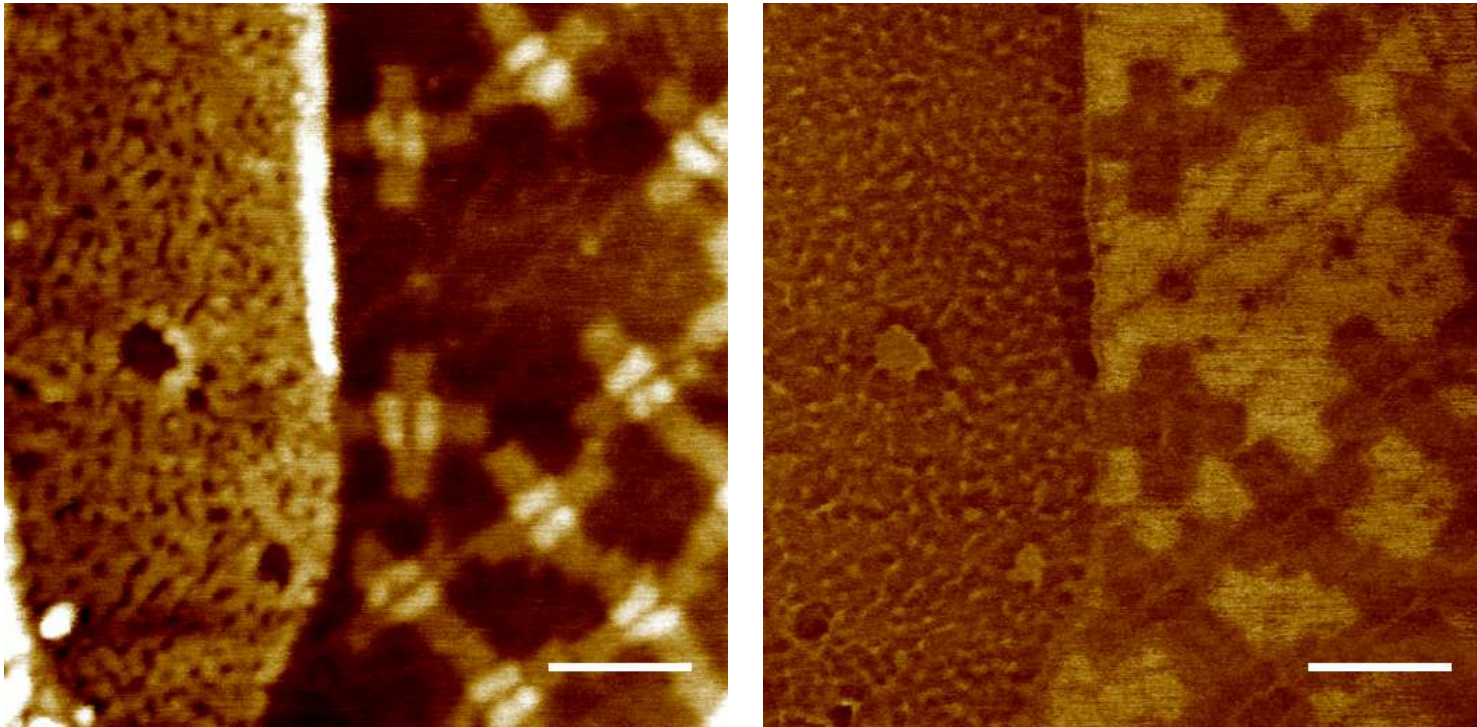
AFM images of cross-shaped DNA origami deposited on graphene-mica substrate. Scale bars, top: 500 nm (AFM lateral), 10 nm (height scale).

DNA origami deposited on graphene-mica

- AFM height (left) and phase (right) images of two separate samples of DNA origami deposited on graphene-mica substrate. Scale bars, 400 nm (AFM lateral); 15 nm (height scale); 30 mV (phase)

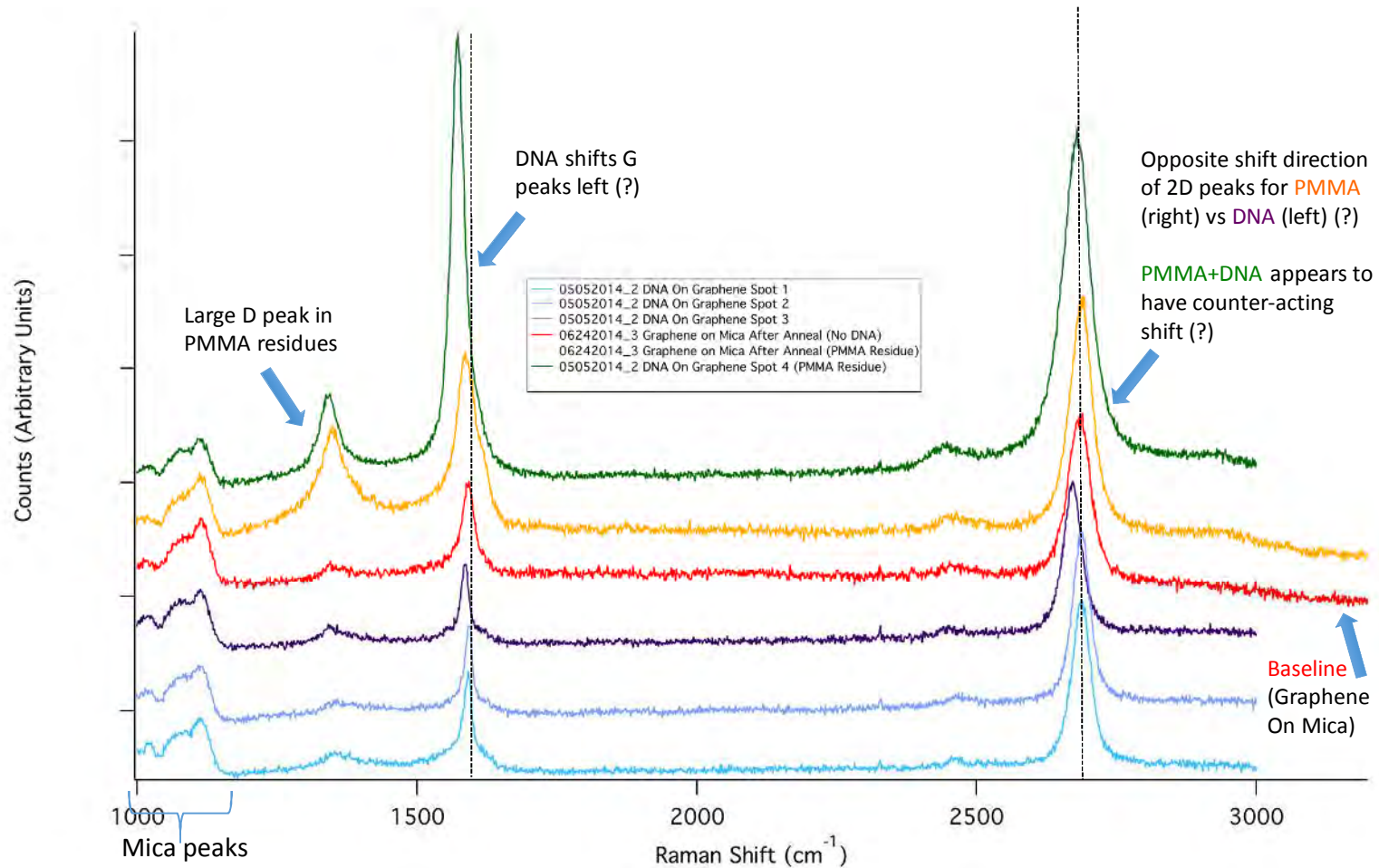


DNA origami deposited on graphene-mica

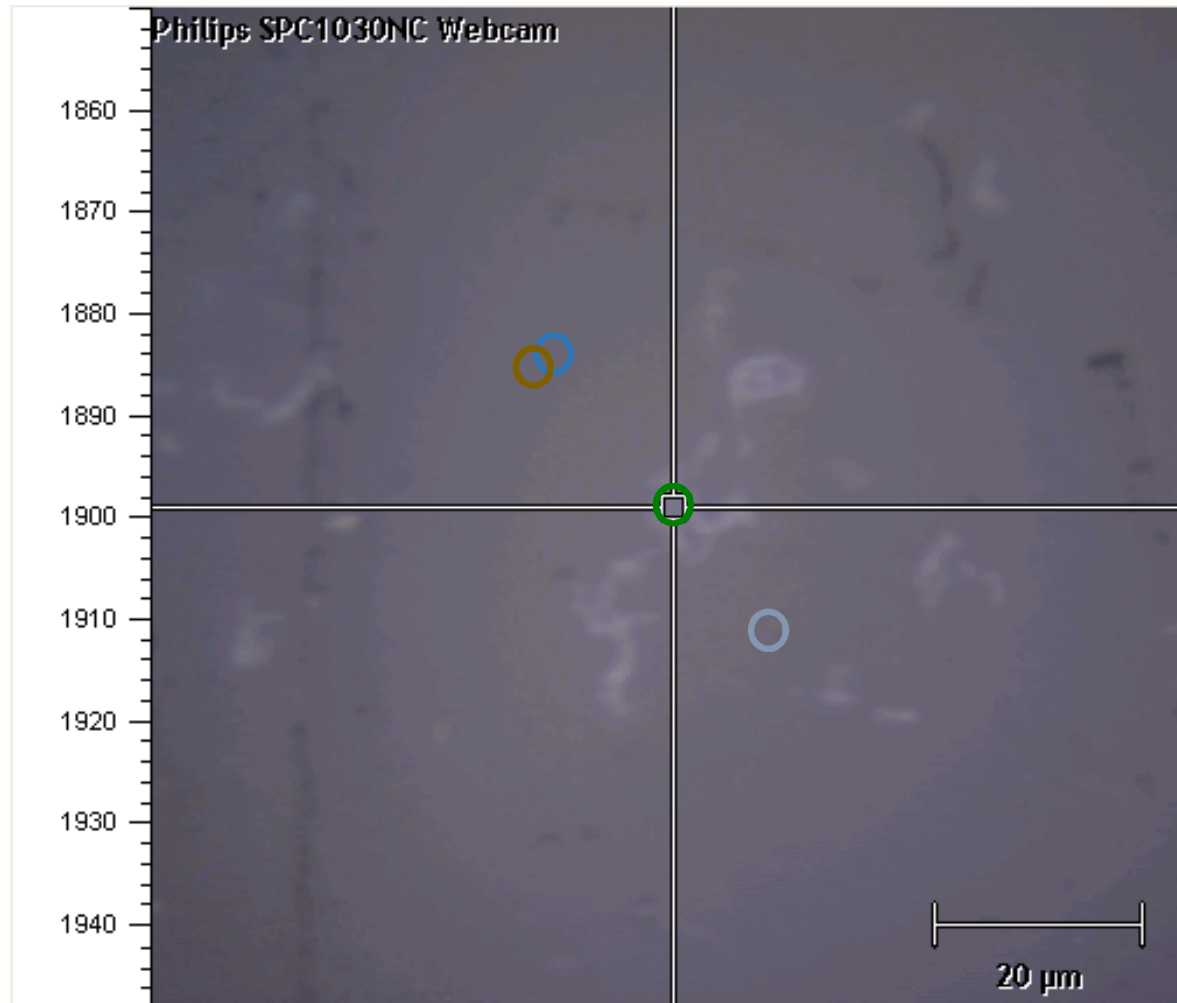


- AFM height (left) and phase (right) image of DNA origami deposited on graphene-mica substrate. Scale bars, 100 nm (AFM lateral); 6 nm (height scale); 30 mV (phase)

Raman spectra of origami on graphene-mica

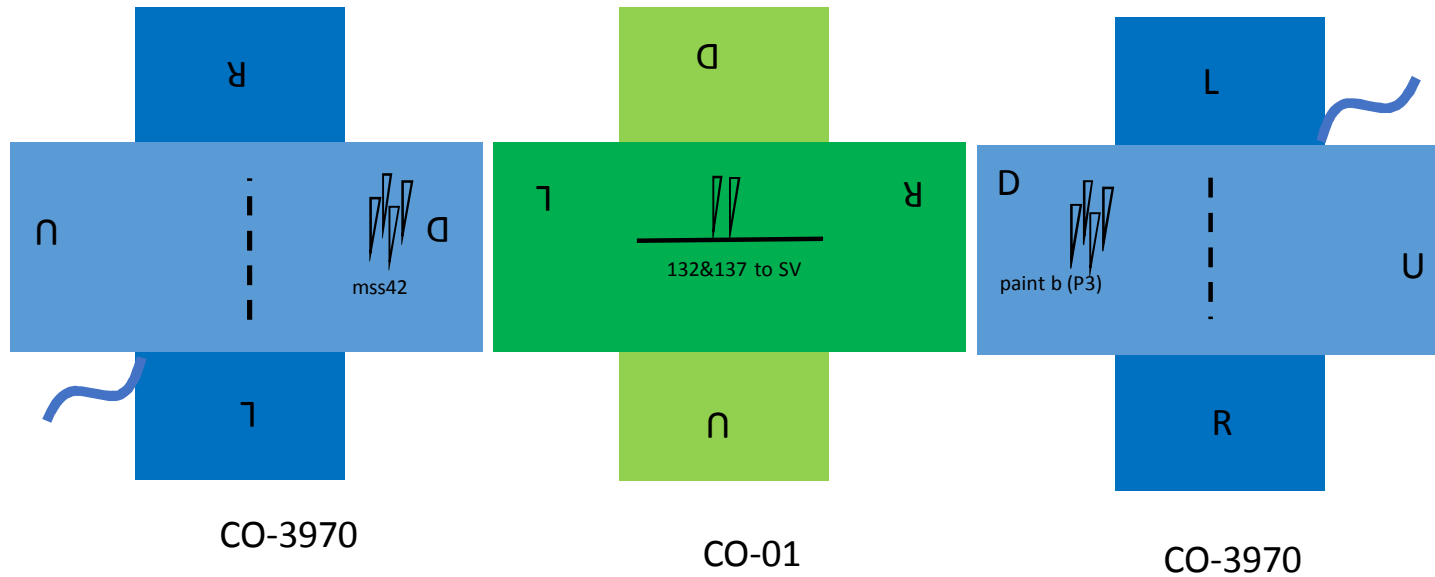


Raman spectra of origami on graphene-mica



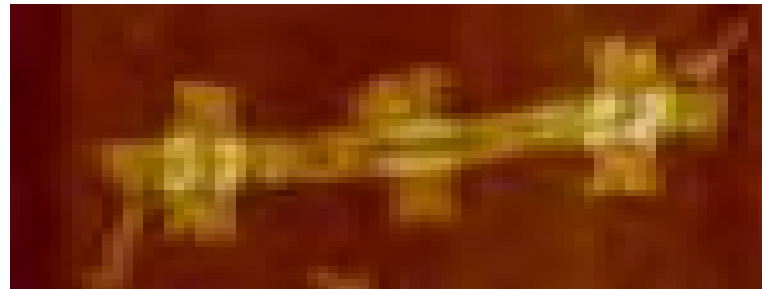
05052014_2 DNA
on Graphene On
Mica (PMMA
Residue in Center)

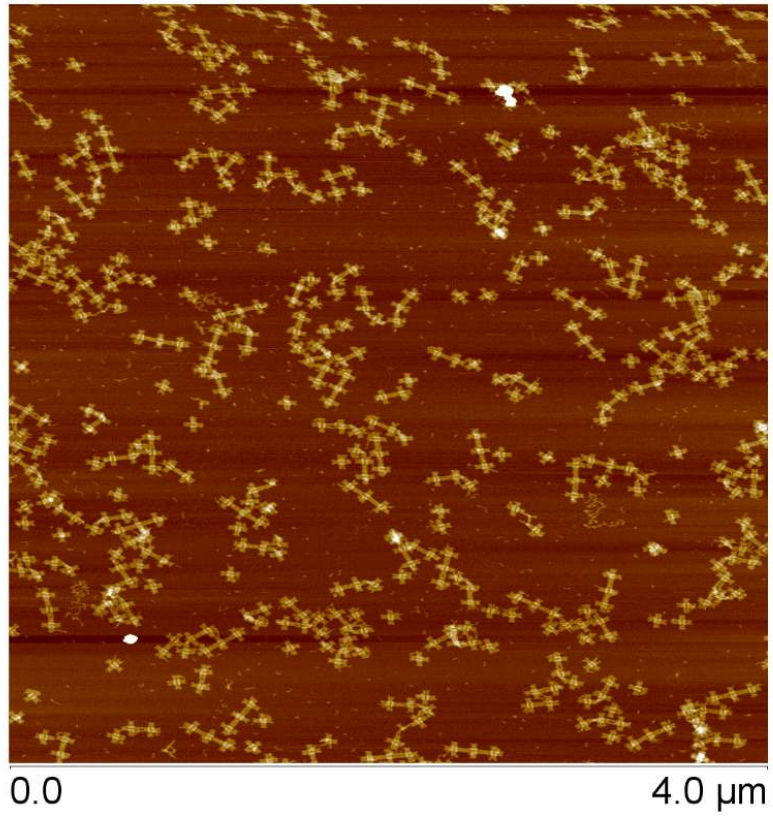




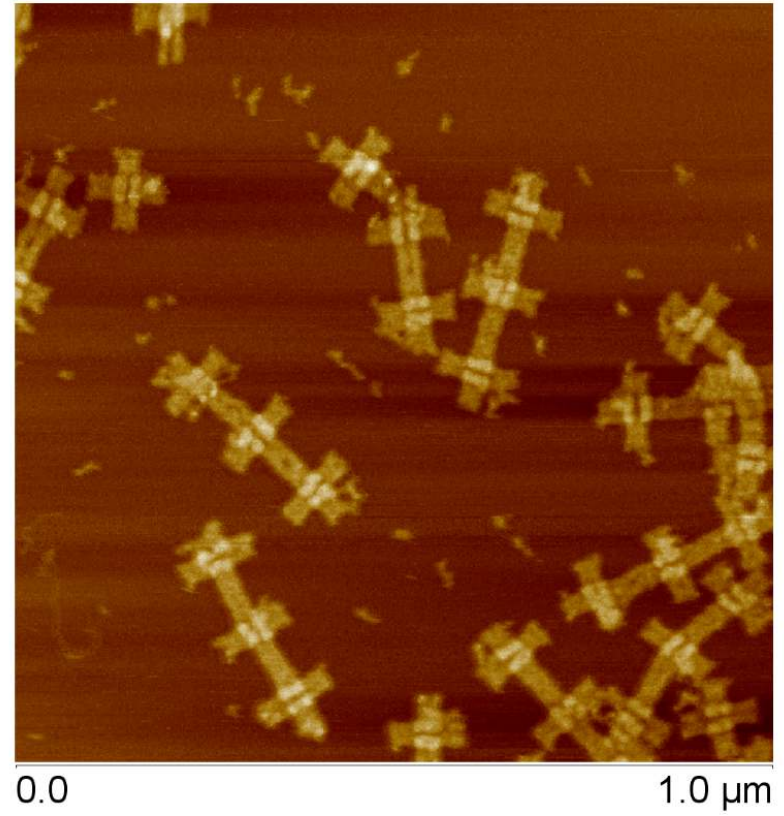
Modifications (shown as triangles projecting from page) from left to right are for AuNP (4), small V origami (2) and dna paint strands for a fluorophore or second AuNP (4).

Location of 'tails' in this construct indicate the orientation of the origami as it lays on the mica surface – in this case, the orientation is the same as that shown in the diagram to left, all mods face 'out of page'





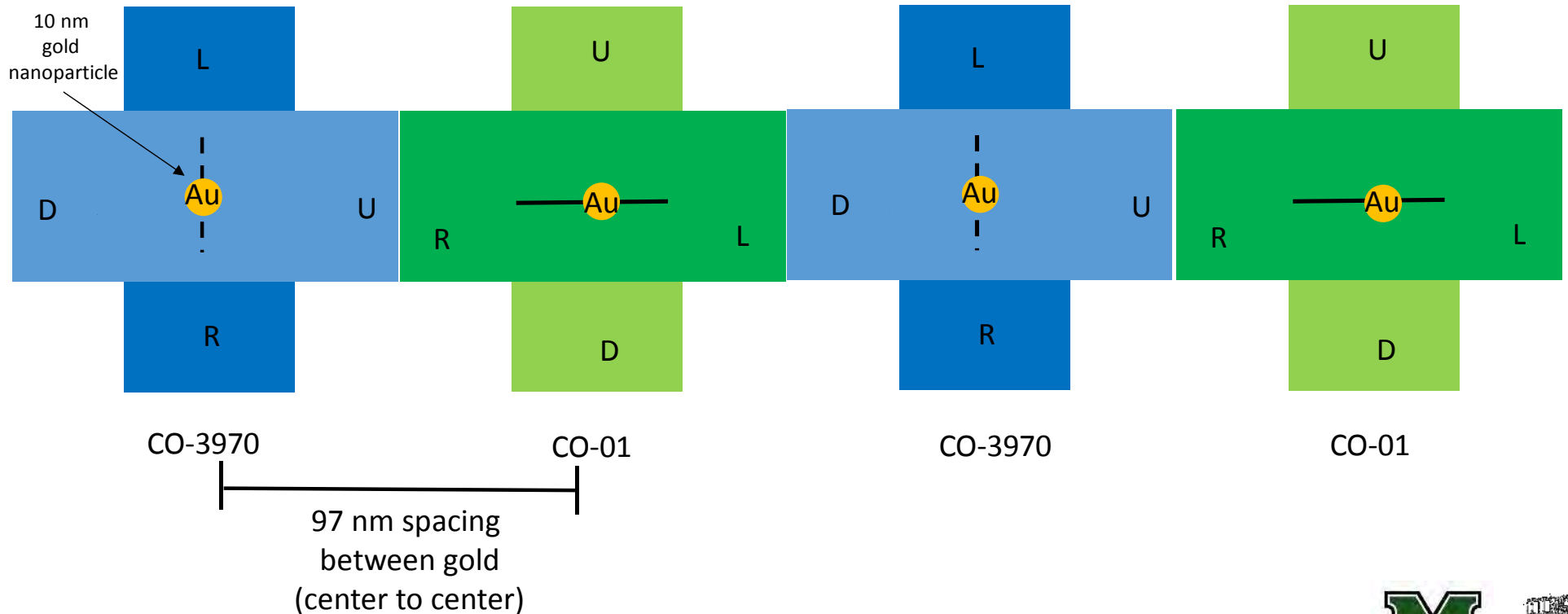
10.0 nm



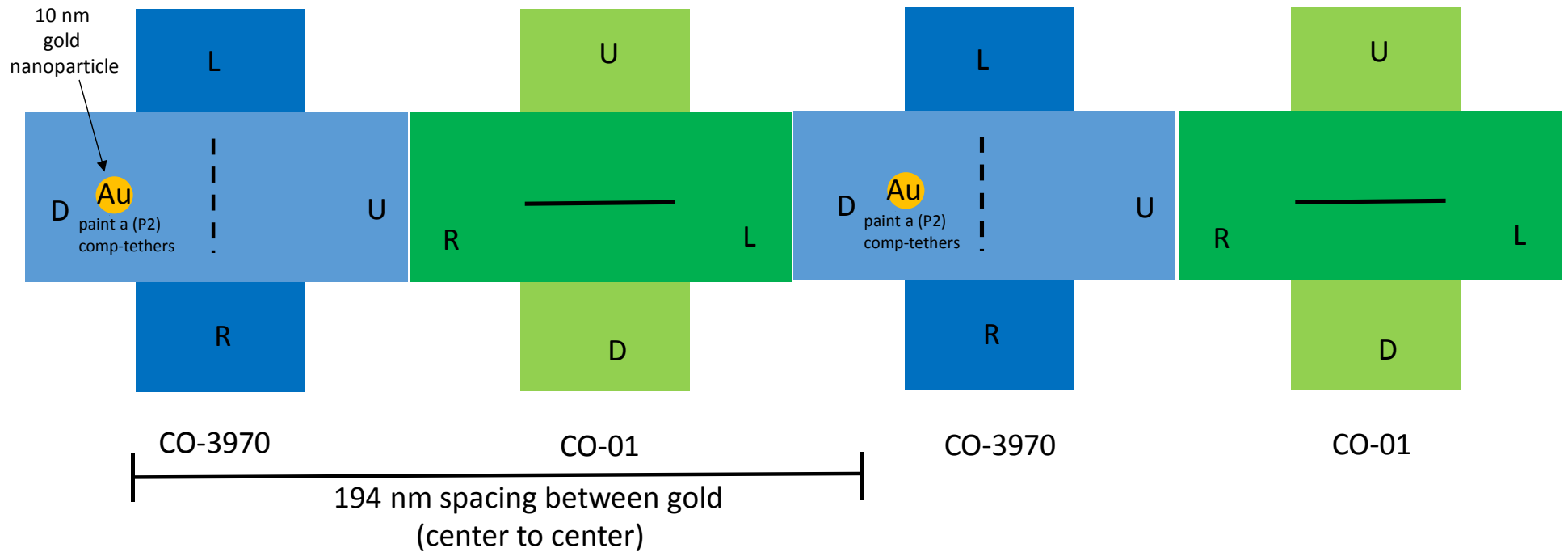
10.0 nm



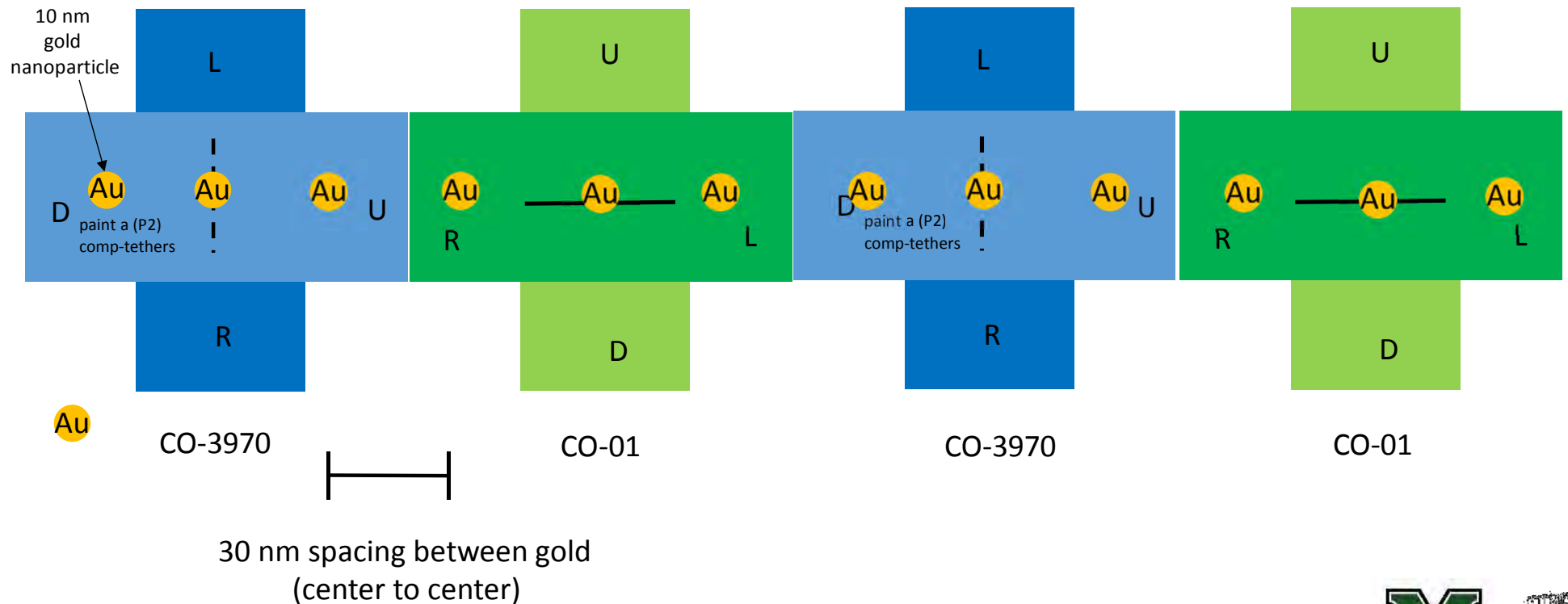
Periodic gold nanoparticles for THz signal (97 nm spacing)



Periodic gold nanoparticles for THz signal (194 nm spacing)

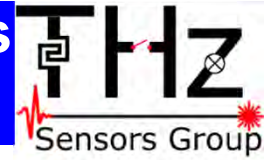


Periodic gold nanoparticles for THz signal (30 nm spacing)





High-Resolution Sensing of DNA Nanostructures and Bioparticles in the THz Region



E. R. Brown, W. Zhang and L. Viveros

also

Peter Burke's Group at U.C. Irvine (for all graphene samples)

Norton's group at Marshall University



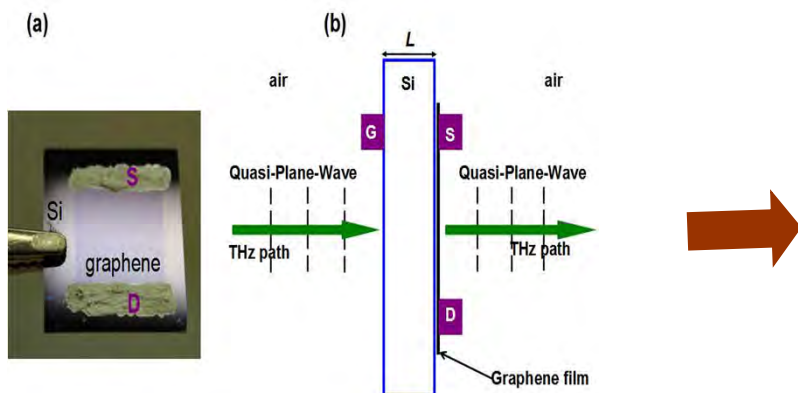
Recent Accomplishments

- Carried out THz characterization of TEST Bed before functionalization: graphene on oxide-silicon (GFET).
- Demonstrate a high amplitude THz modulation ($\geq 20\%$ depth-of-modulation).

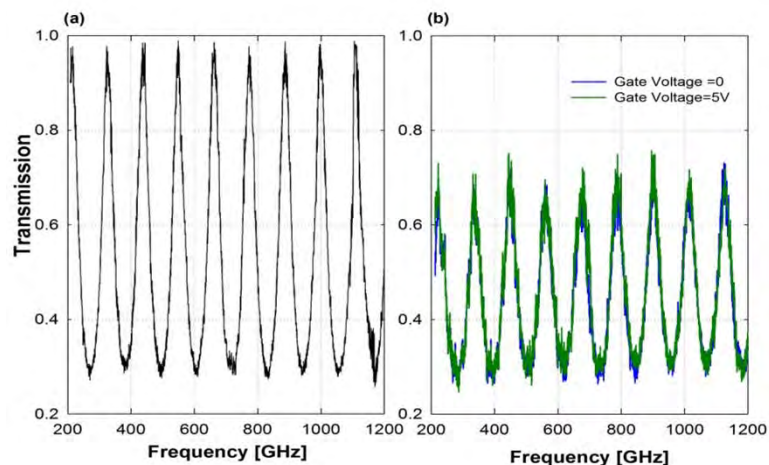


Broadband THz Conductivity of 2D Material

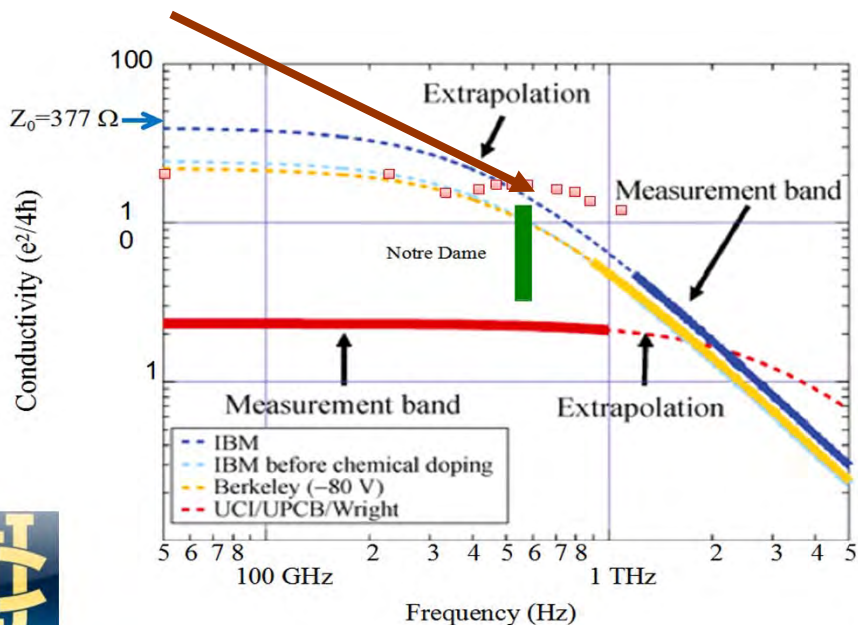
Non destructive setup



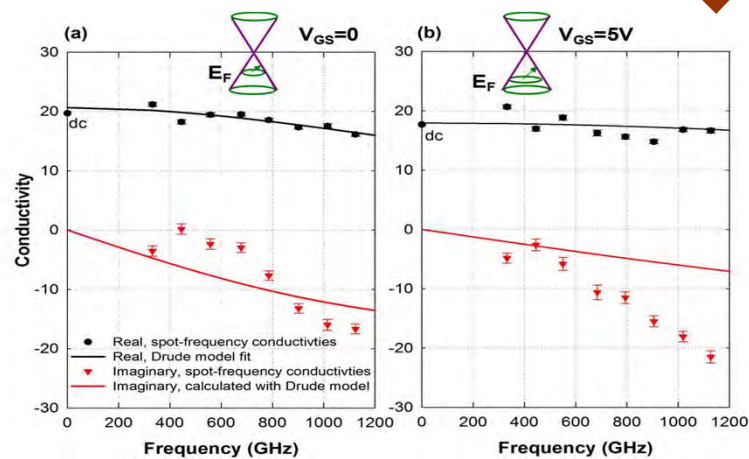
THz spectrum (raw)



WSU/UCI data



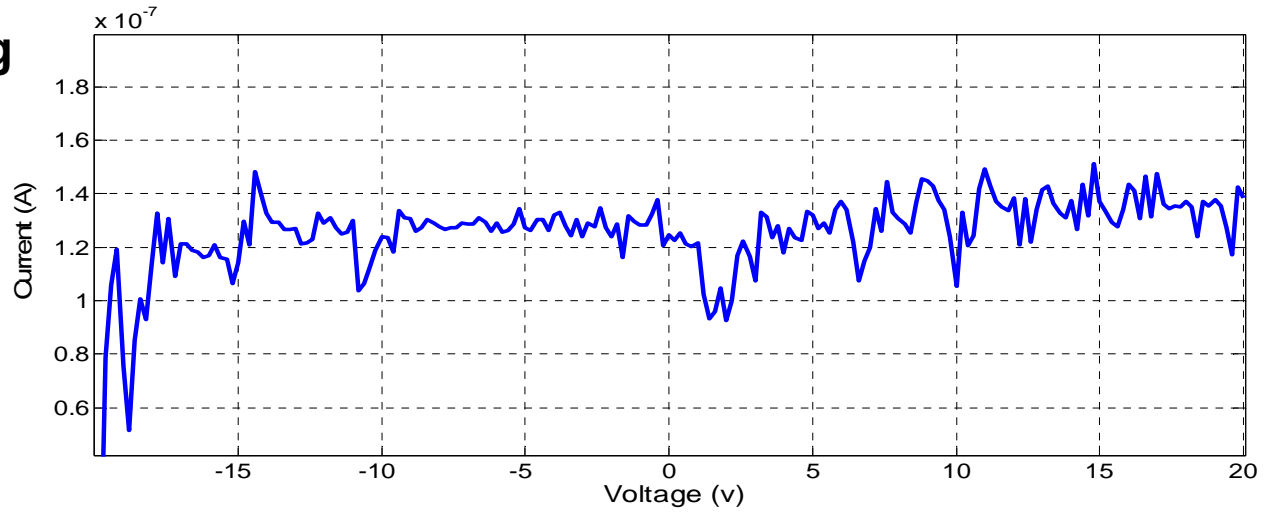
Extracted THz conductivity (with TM/TL method)



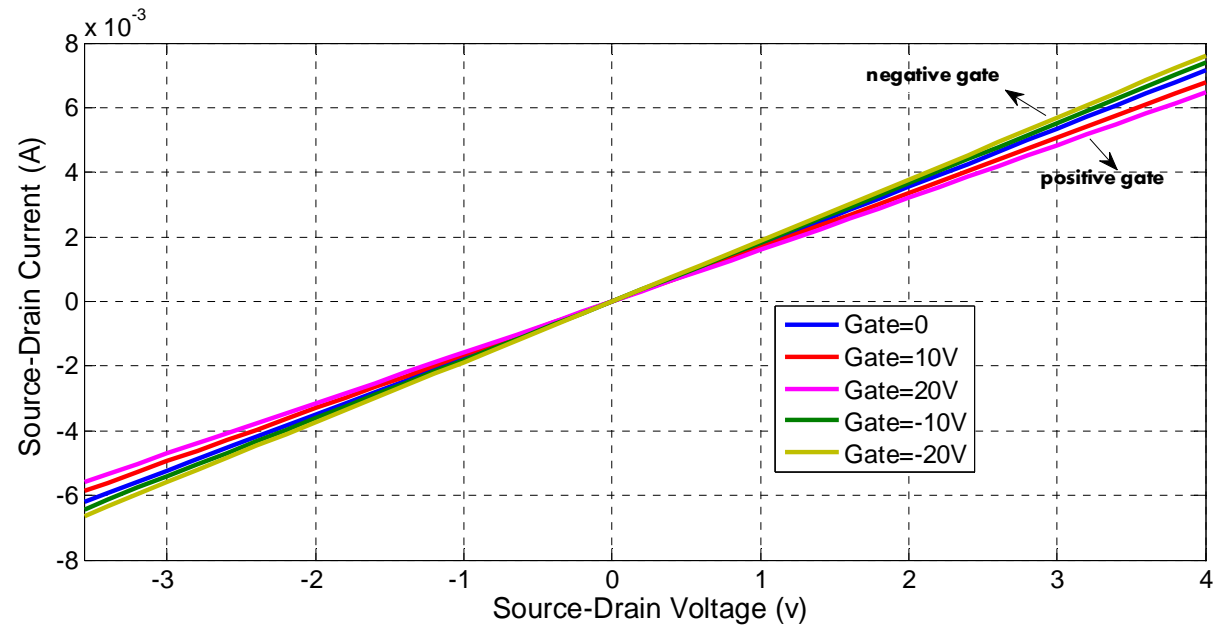
A paper has been submitted to nanoscale

DC Properties of a New GFET

Small gate leaking

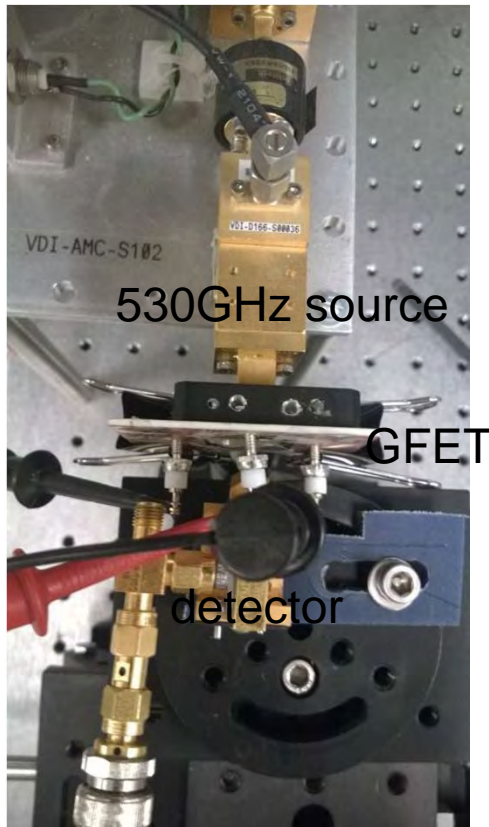


Good transconductance

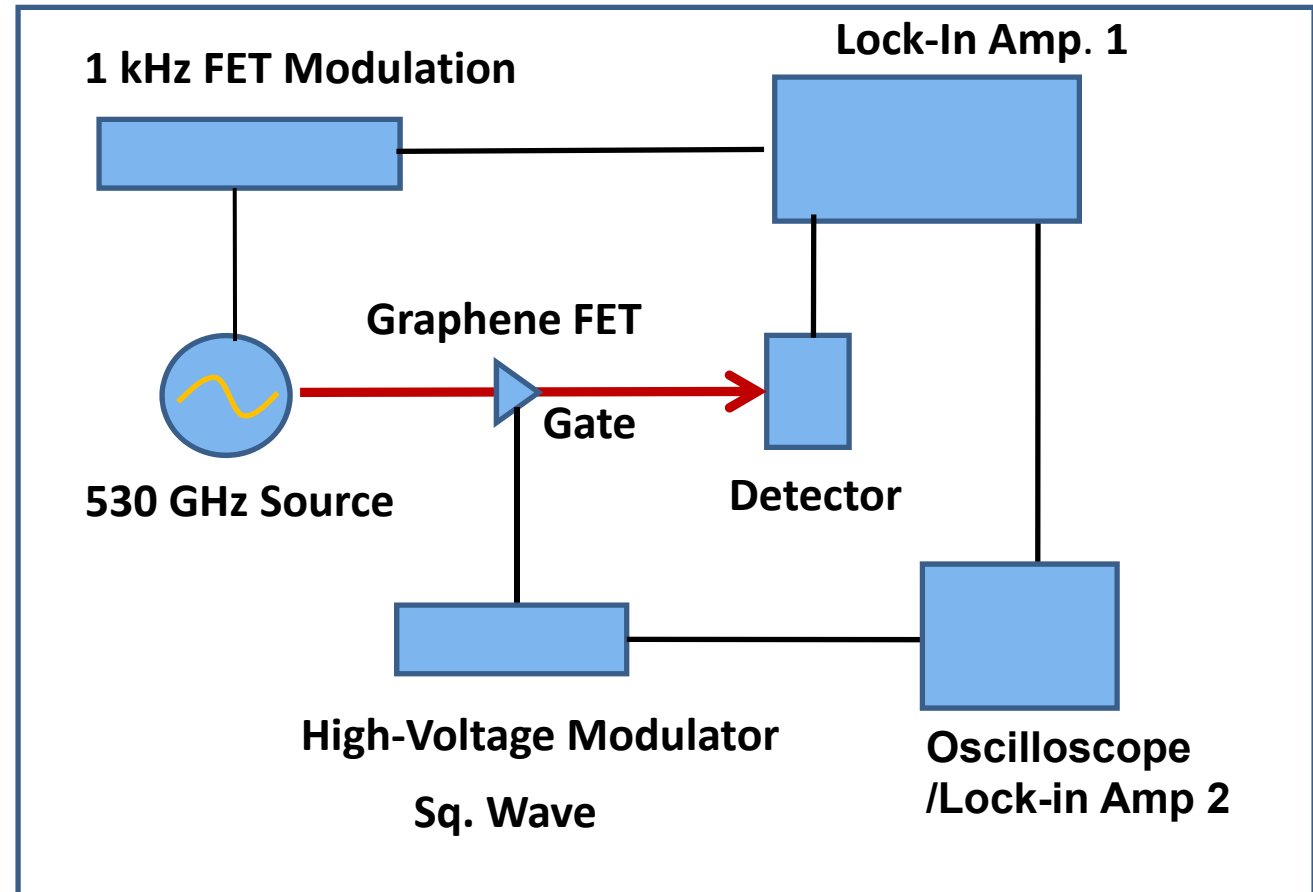


Demonstration of THz (530 GHz) Gate-Voltage-Controlled Modulation

- Source: 530 GHz FEM
- Detector: Schottky Diode



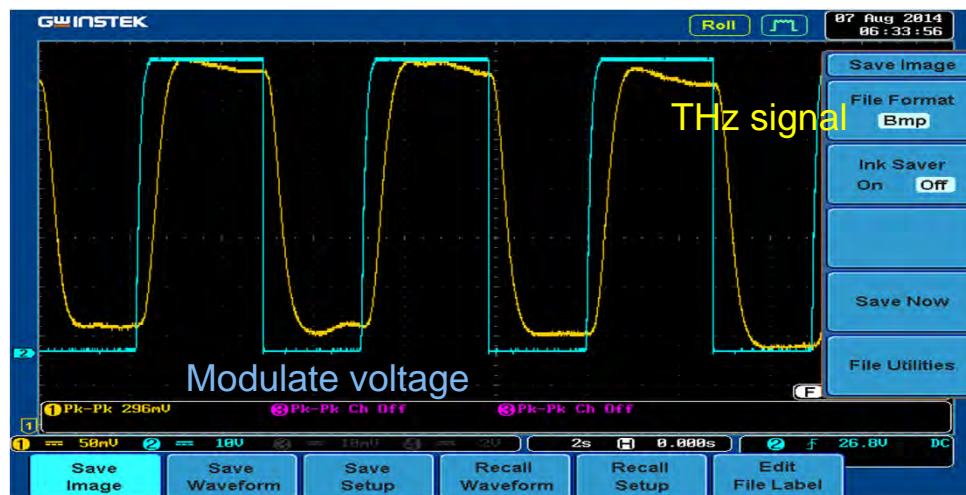
Double-Modulation Approach



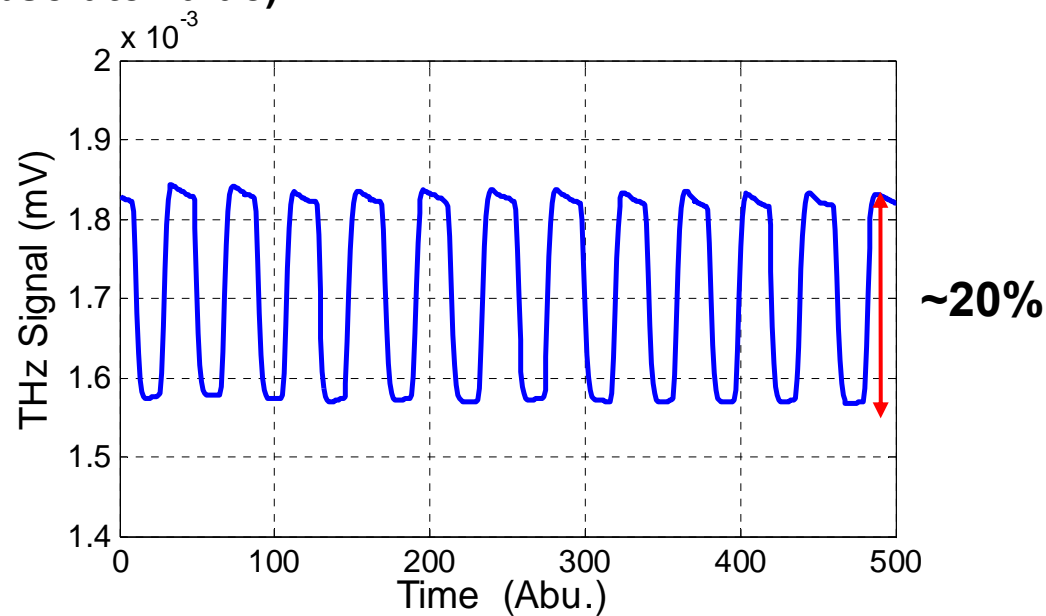
20% THz (530 GHz) Depth-of-Modulation

$$f_m = 0.2 \text{ Hz}$$

$$V_{amp} = 60 \text{ V}$$

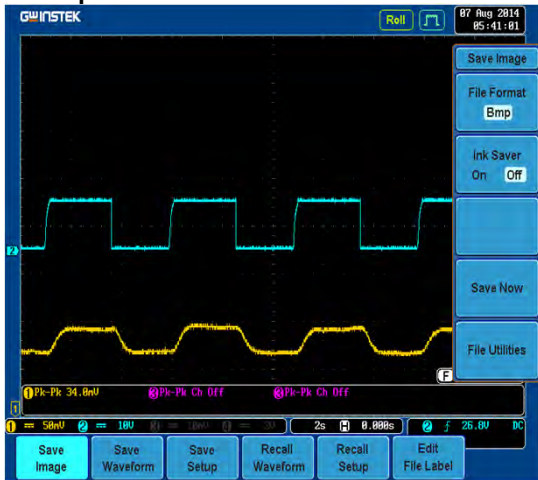


THz Signal Modulation (absolute value)

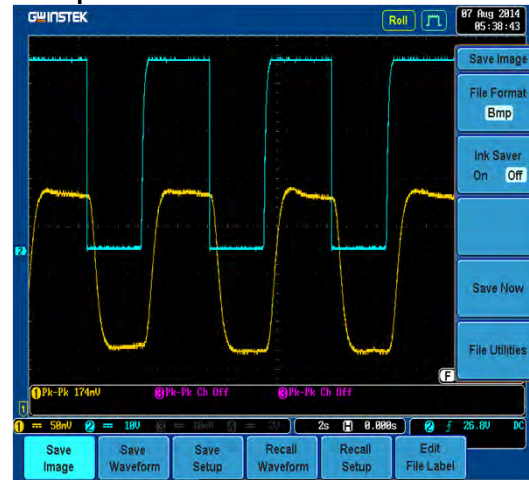


The Modulation vs. Gate Bias

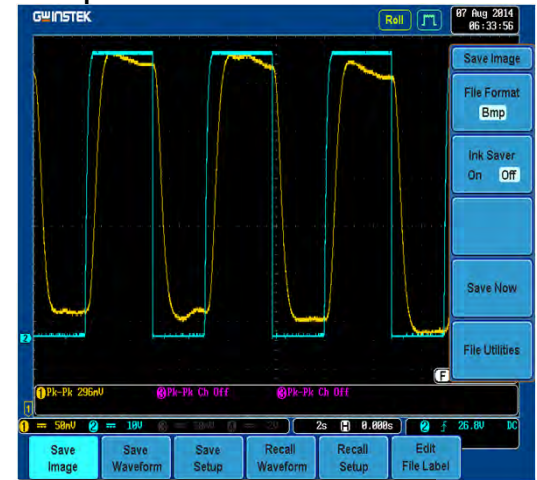
$f_m = 0.2 \text{ Hz}$
 $V_{amp} = 10V$



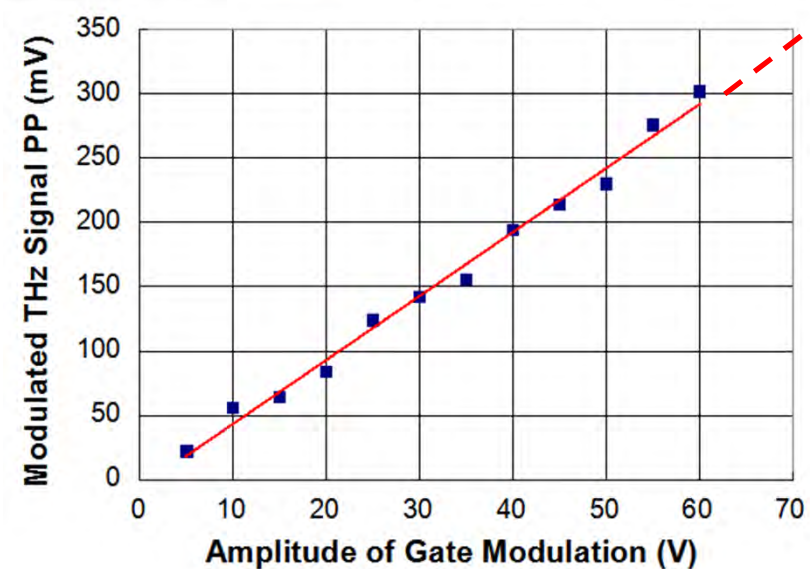
$f_m = 0.2 \text{ Hz}$
 $V_{amp} = 40V$



$f_m = 0.2 \text{ Hz}$
 $V_{amp} = 60V$

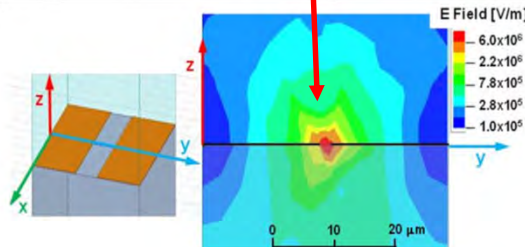


- Modulation (pk-pk) increases as gate bias increases
- Narrow bandwidth: 1Hz



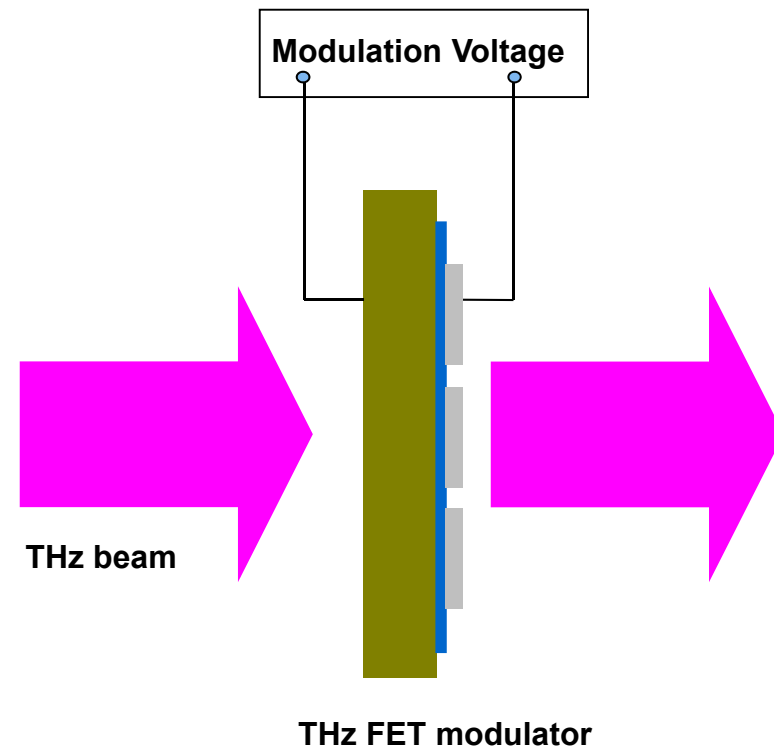
The Design of THz Modulator with Grid Electrodes

Surface-current concentration effect
(structured-surface plasmons)
can greatly enhance THz E field and intensity
in deep sub- λ apertures



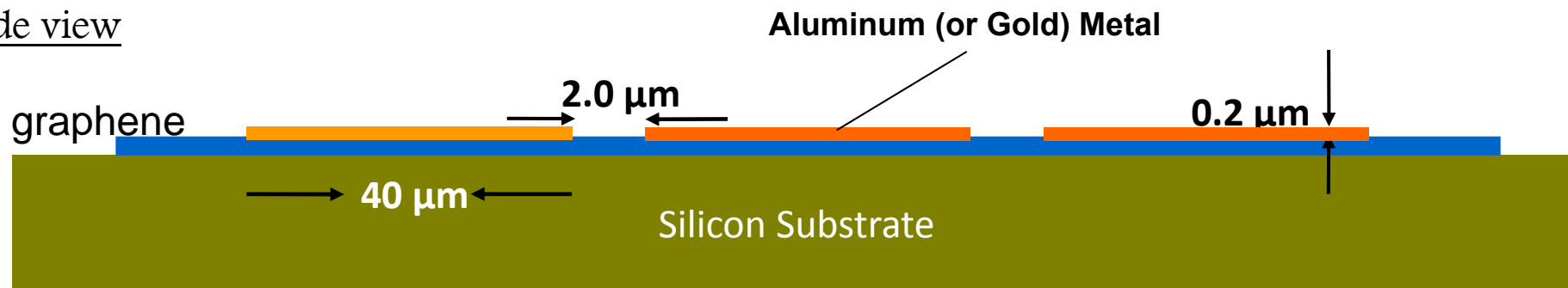
Combine structured surface plasmon THz coupler with GFET

For (1) Modulator (2) THz Plasmonics



The Modulator Layout

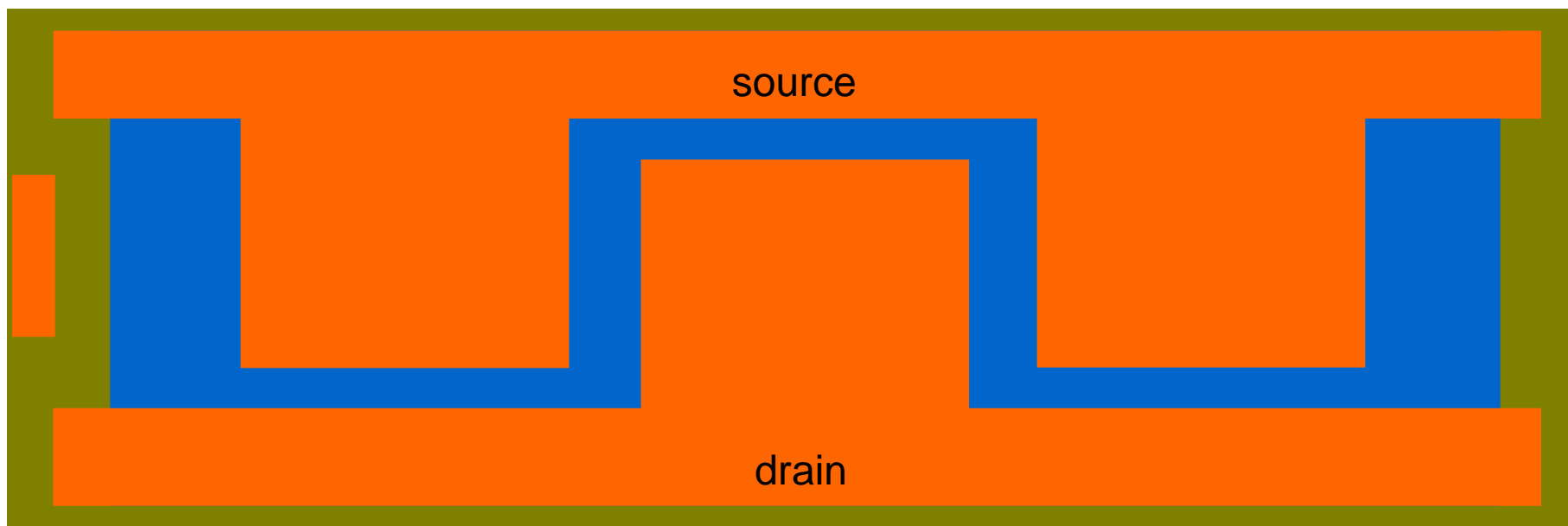
side view



top view

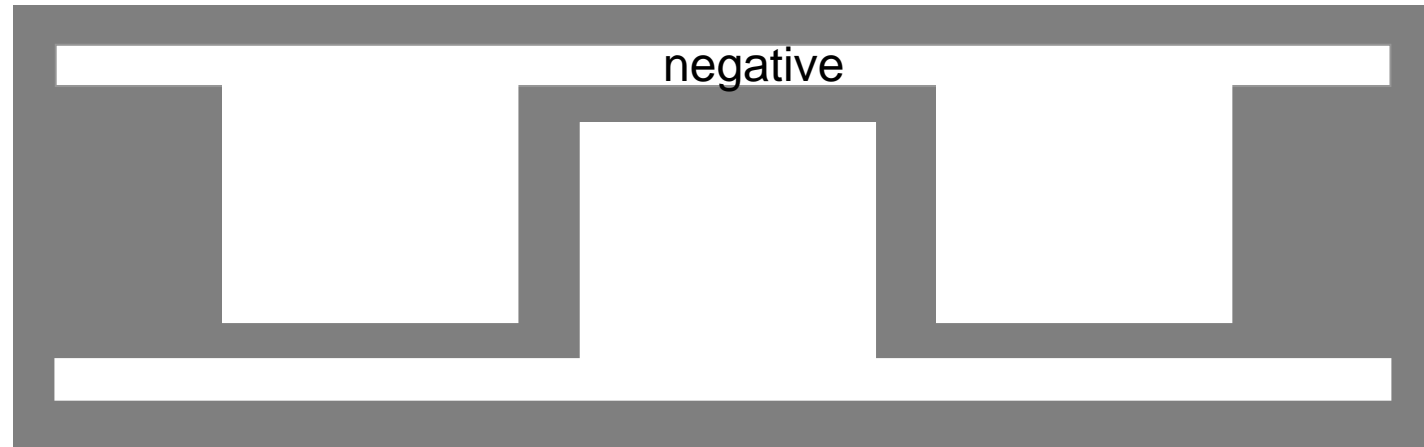
 Al or Au Strip

side/back gate

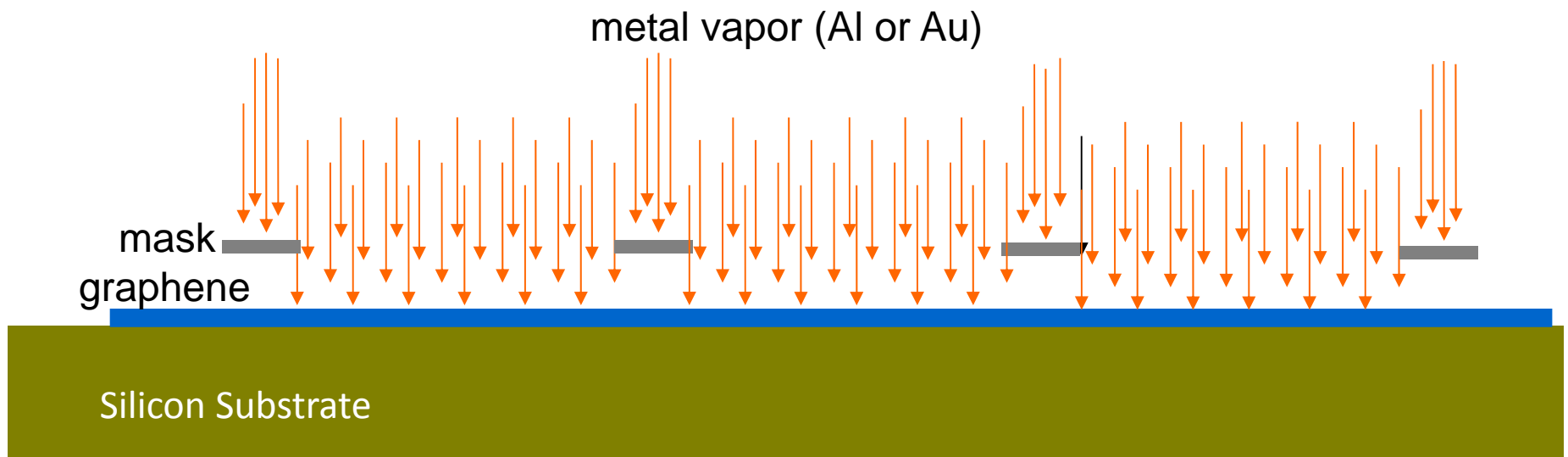


Stencil Processing

Stencil mask



Stencil lithography



Conference Proceedings:

- "AC Conductivity Parameters of Graphene Films with THz Spectroscopy ," W-D. Zhang, E. R. Brown, Phi H. O. Pham and P. Burke, NAECON Conference, Dayton, June 25-27, 2014.
- "Bio-Inspired THz Applications for Microorganism Fingerprinting", L. Viveros, A. Bykhovski , W-D. Zhang, and E. R. Brown, NAECON Conference, Dayton, June 25-27, 2014.
- "Concentration of Terahertz Radiation for Microsample Spectroscopy," W-D. Zhang, L. Viveros , E. R. Brown to be presented at IRMMW-THz Symposium, Tucson, AZ, September 14-19, 2014.

Journal Papers:

- "AC Conductivity Parameters of Graphene Derived from THz Etalon Transmittance" W-D. Zhang, Phi H. O. Pham, E. R. Brown, and P. Burke, Nanoscale, under review.
- "Experiment and Simulation for the strong Low-Terahertz Absorption of Thymine Monohydrate", L. Viveros, A. Bykhovski , W-D. Zhang, and E. R. Brown, to be submitted.