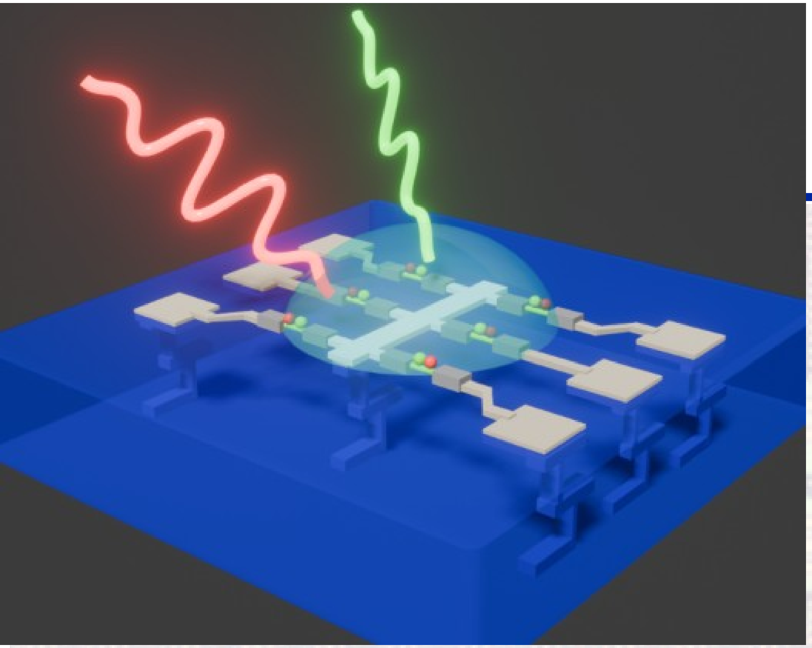
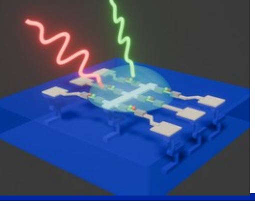


Nanoscale Hybrids:
A new paradigm for energy efficient microelecronics

MEERCAT Meeting, May 28, 2025



Energy Efficient How?

BEFORE

sensors

Triggerless
Raw
Petabytes

computing

power

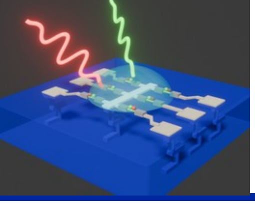
AFTER

Novel
sensors

Pre-
processed
information

computing

power



Energy Efficient How?

BEFORE

sensors

Triggerless
Raw
Petabytes

computing

power

Not dreaming of a new computer that can do the same job with less power

It's the needed computing that has been reduced

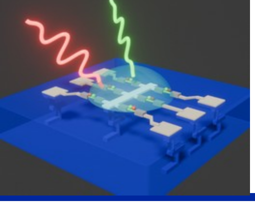
AFTER

Novel
sensors

Pre-processed information

computing

power



Energy Efficient How?

BEFORE

sensors

Triggerless
Raw
Petabytes

computing

power

AFTER

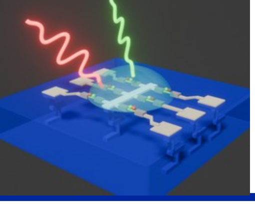
Novel
sensors

Not inserting edge computing here to eliminate data transmission / storage but still do the same computations

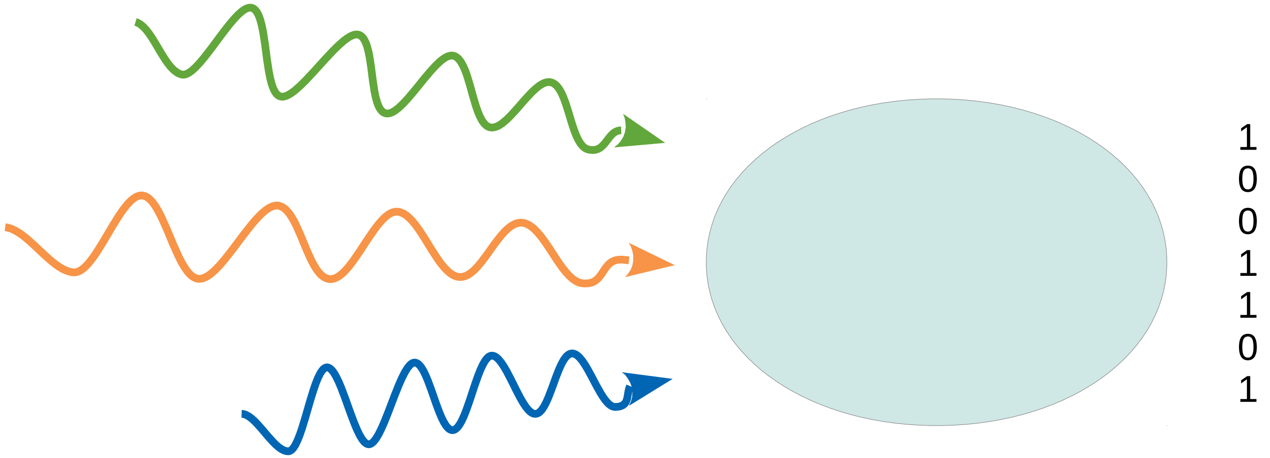
Pre-
processed
information

computing

power



A new kind of sensor where the raw output is programmable/trainable information



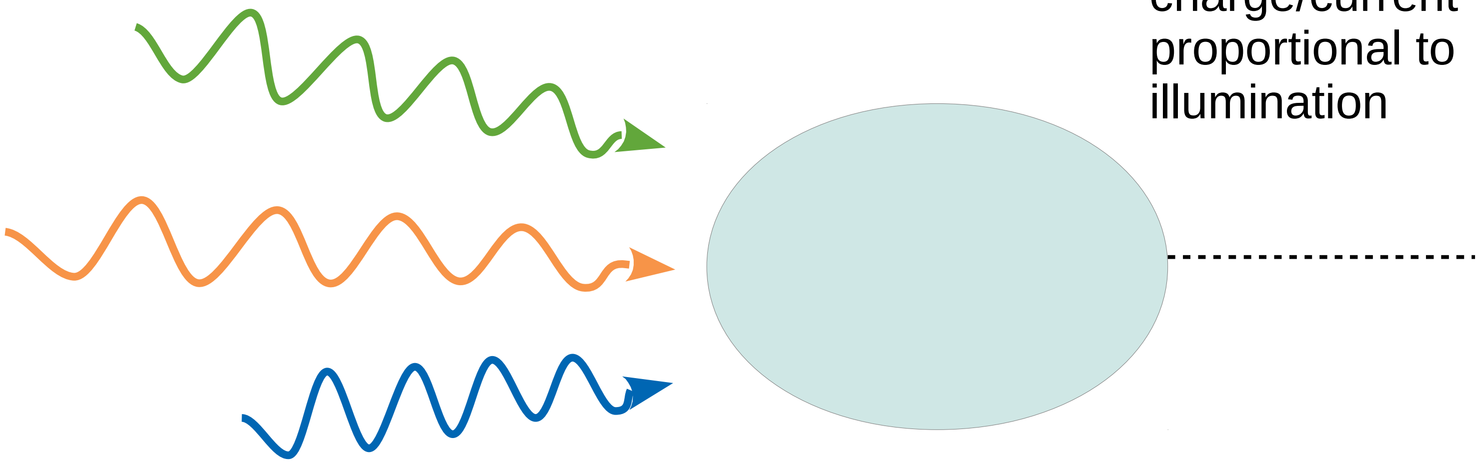
Photon field

Information

1
0
0
1
1
0
1

Edge computing, if present
Would go here

Consider silicon



Photon field

Outputs electric charge/current proportional to illumination

Raw output has to be processed to extract information

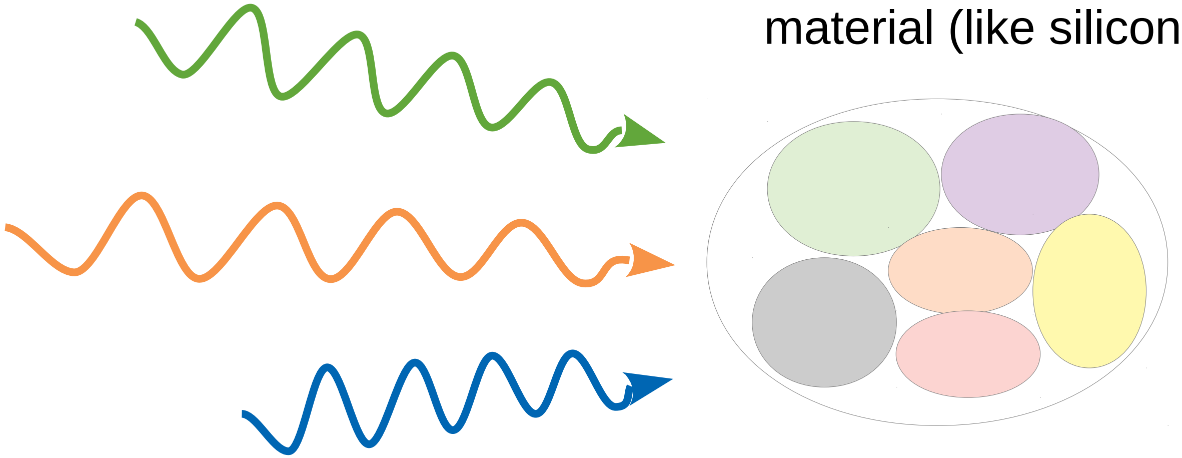
Can’t train silicon to respond differently today than it did yesterday.

Response given by material properties

A nanoscale hybrid is an artificial material

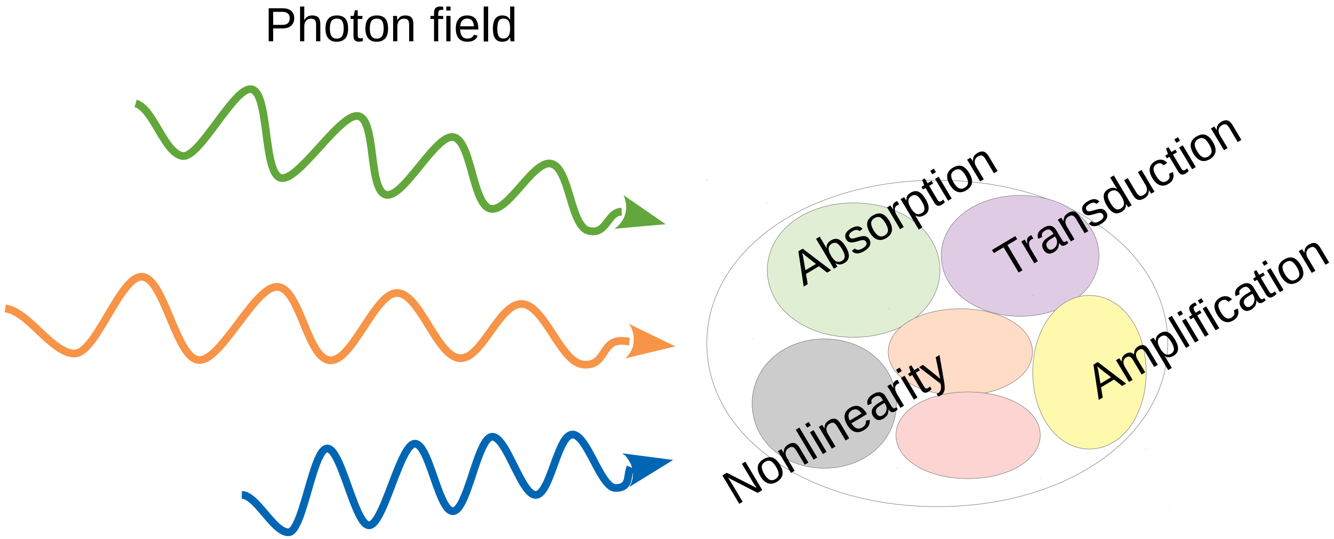
Made up of separate
elements smaller than incoming wavelength

As far as the light is concerned this is one
material (like silicon). Can’t resolve the elements

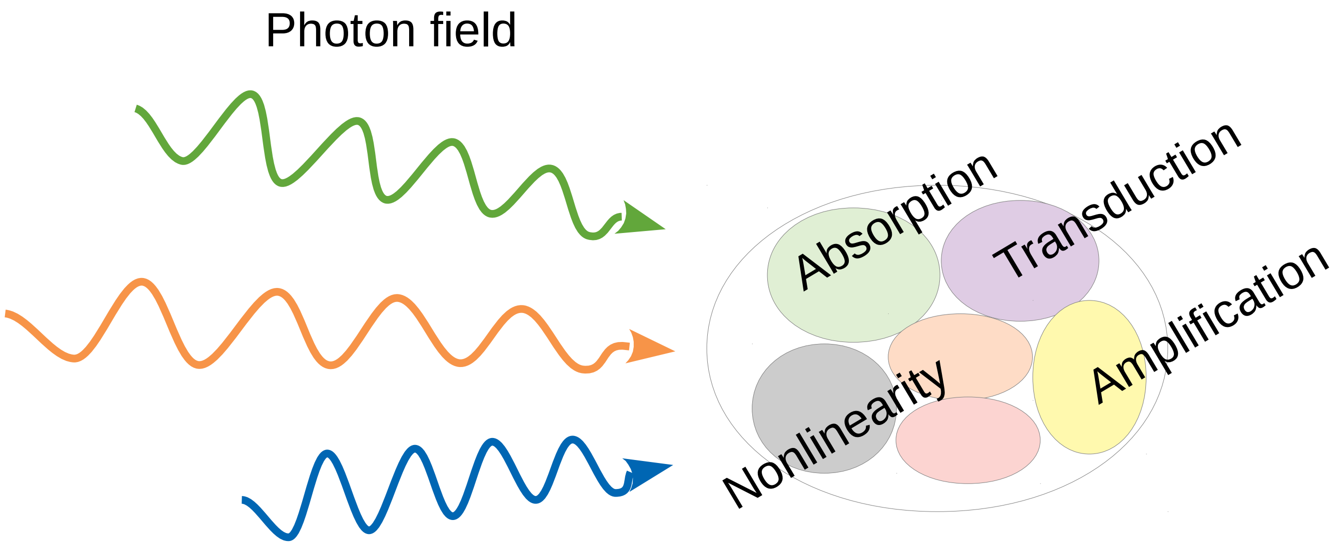


Independent control of interactions

UNLIKE any natural material (like silicon)



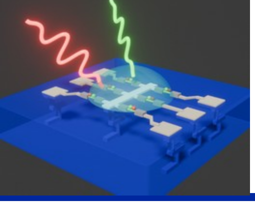
Independent control of interactions

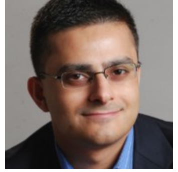


Can optimize the sensing process- extract the maximum possible information form the photon field (see later slide on theoretical foundation)

In this project we aim to go further, and use the nanoscale hybrid also to process information, ideally in a programmable way.
MAKE AN ARTIFICIAL “MATERIAL” THAT CAN LEARN

“MATERIAL” as far as light is concerned



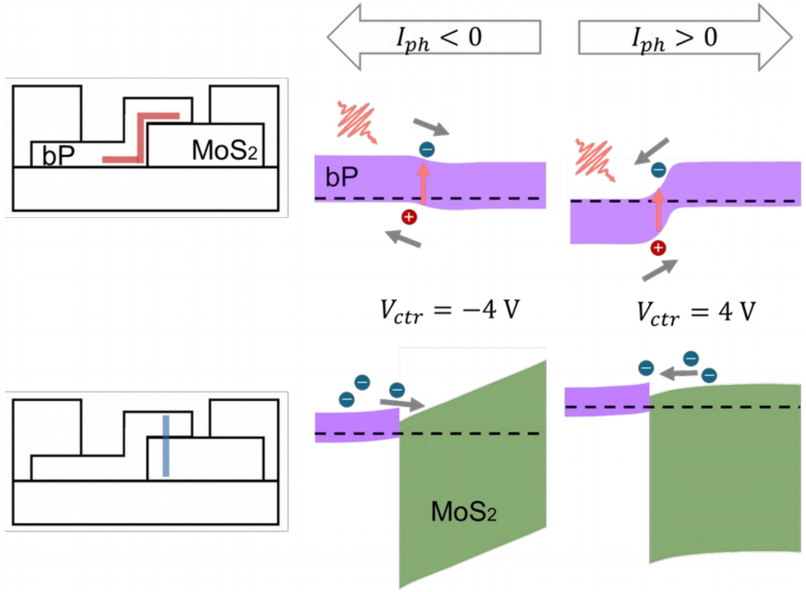


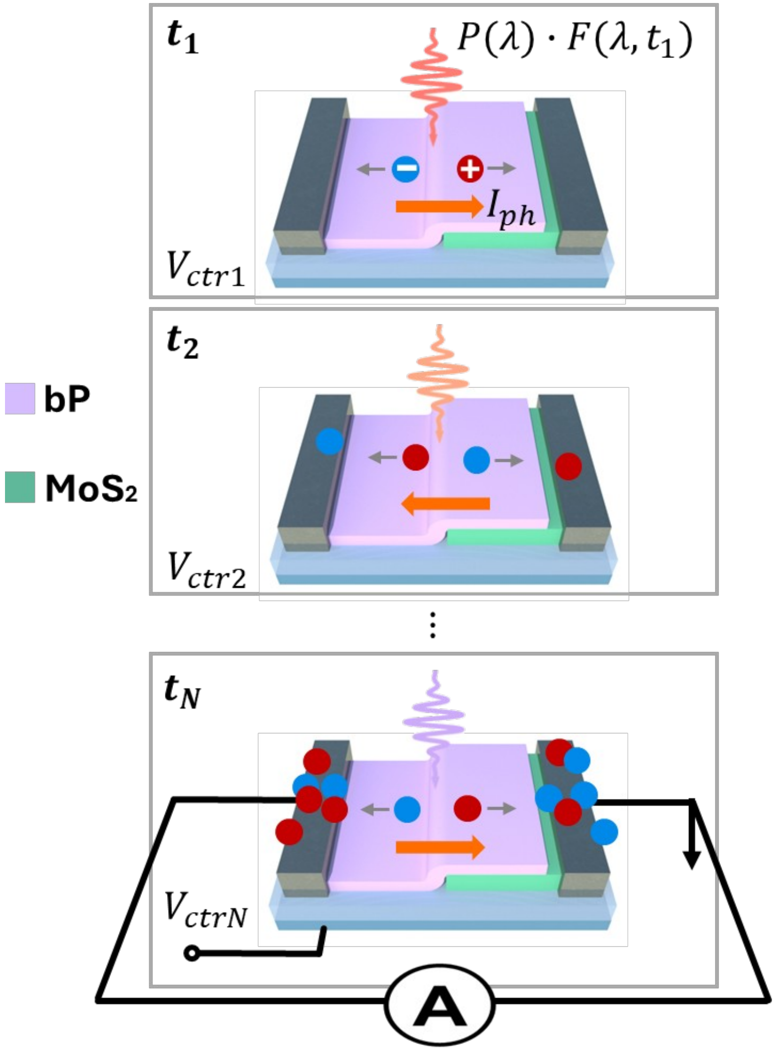
PI Ali Javey

Example of pretty smart sensor without nanoscale hybrids

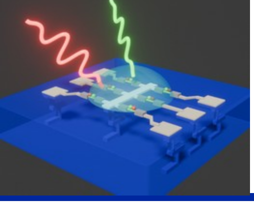
Tunable Bipolar Photodiode

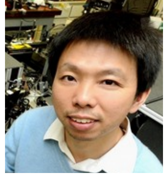
- Electrically tunable.
- Bipolar: charge polarity given by photon wavelength





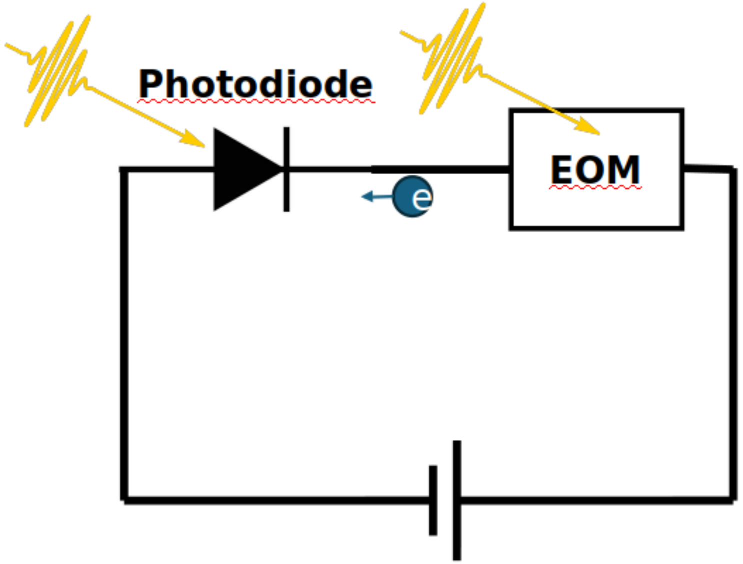
But still subject to bulk material properties **(bP=plack phosphorus)**





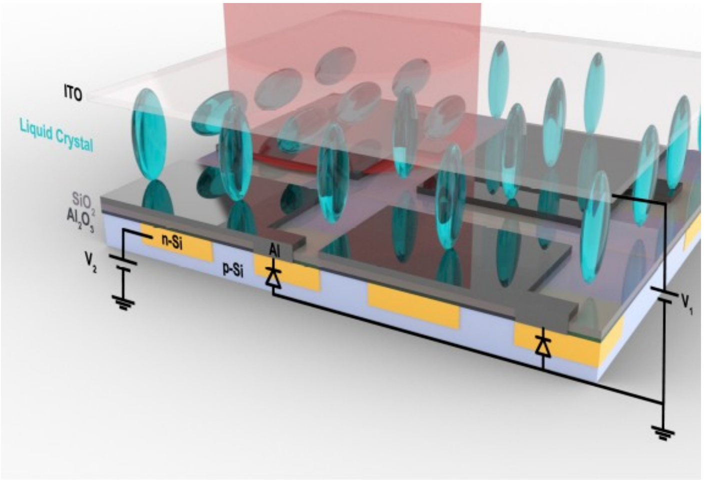
PI Feng Wang

Example of in-sensor learning without nanoscale hybrids

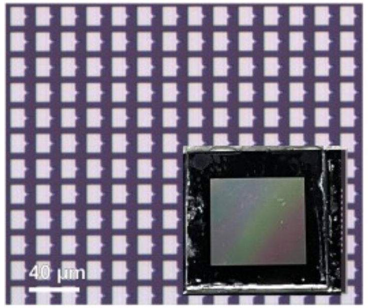


Engineered Optical Nonlinearity
- Low power consumption
- Compatible with incoherent light
- CMOS compatibility

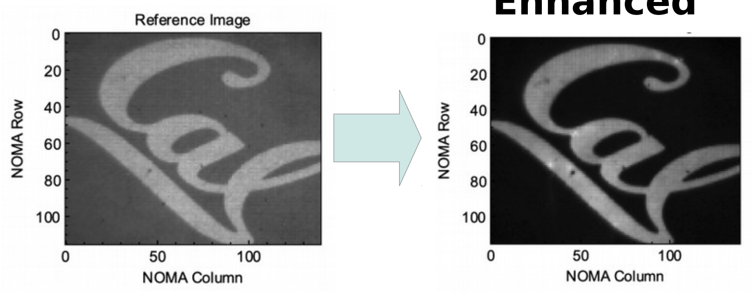
0.5 Mpixel array on CMOS implementation



Basic structure:
- Liquid crystal for EO modulation
- Silicon photodiodes array for light detection

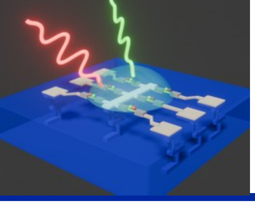


Real-time Contrast Enhanced



- But this involves an electrical feedback loop.
- We aim to implement such feedback in couplings between nanoscale elements- before transduction to electrical signals

Qixin Feng et al. ,Femtojoule optical nonlinearity for deep learning with incoherent illumination.Sci. Adv.11,eads4224(2025)



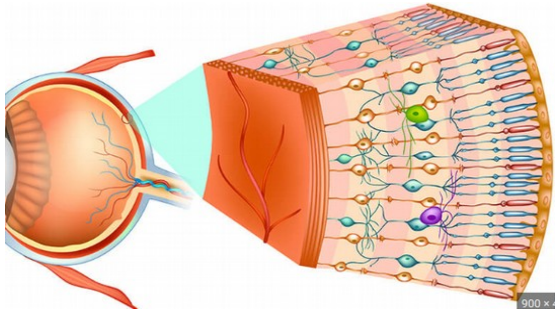
Longer term concept development

Novel sensors

Pre-processed information

computing

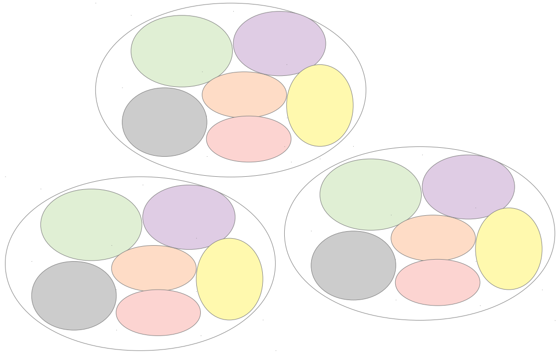
power



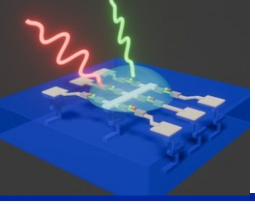
Pre-processed information

computing

power



Need interactions between multiple nanoscale hybrids to form a network

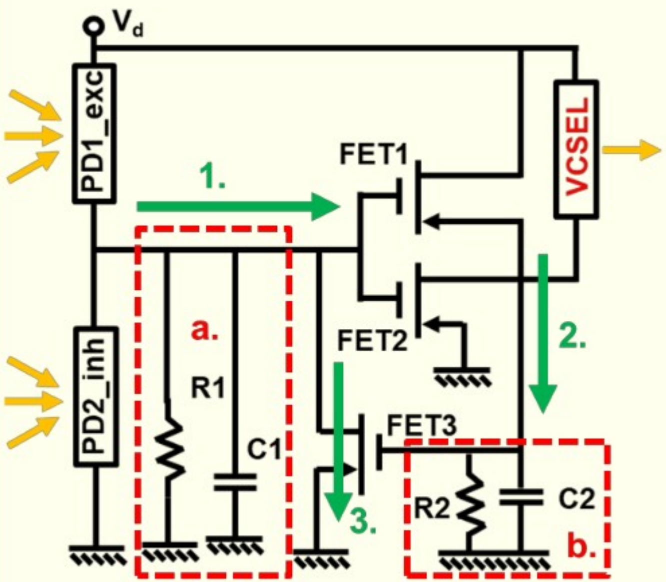


PI S. J. Ben Yoo

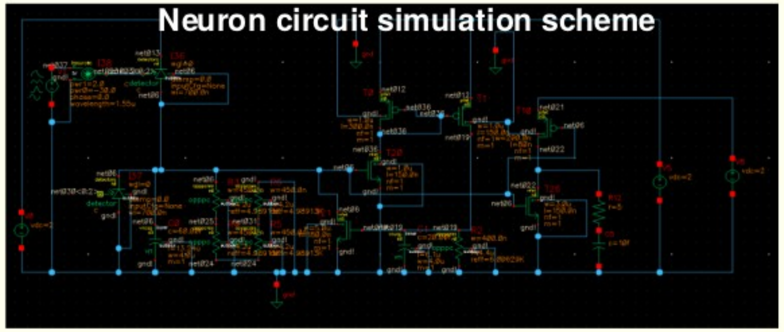
Example of network without nanoscale hybrids

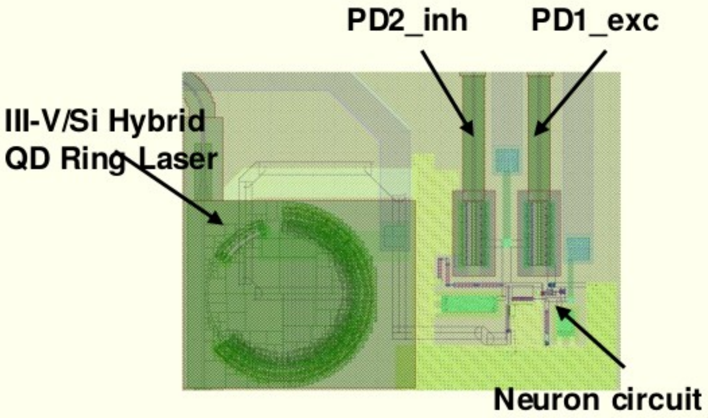
Optoelectronic Neurons: towards Nano-Scale Attojoule Optoelectronic Neurons

Testbed Implementation optoelectronic neurons

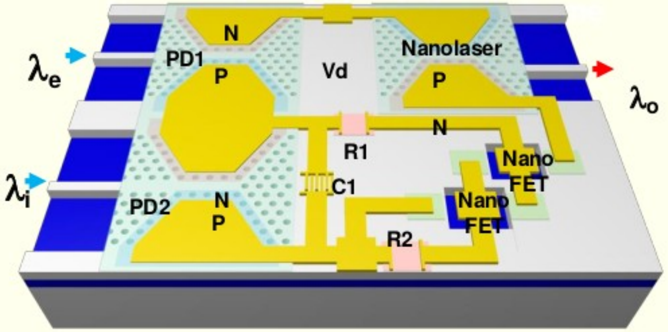


Foundry Implementation micron-scale optoelectronic neurons

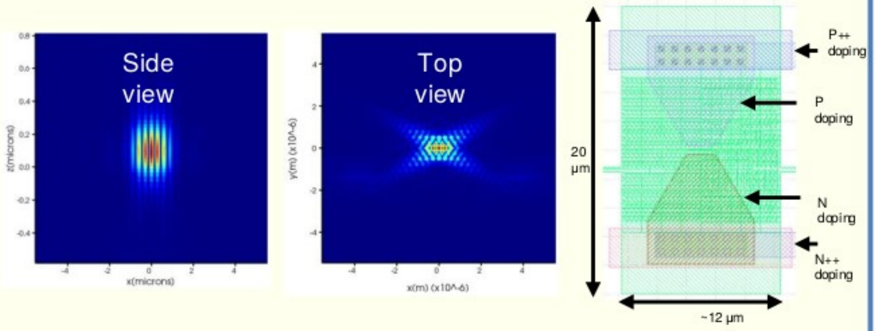




Future Nano-scale attojoule optoelectronic neurons



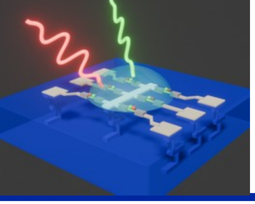
III-V/Si Hybrid QD Photonic Crystal Lasers



Similar structures for Photonic Crystal Photo Detectors

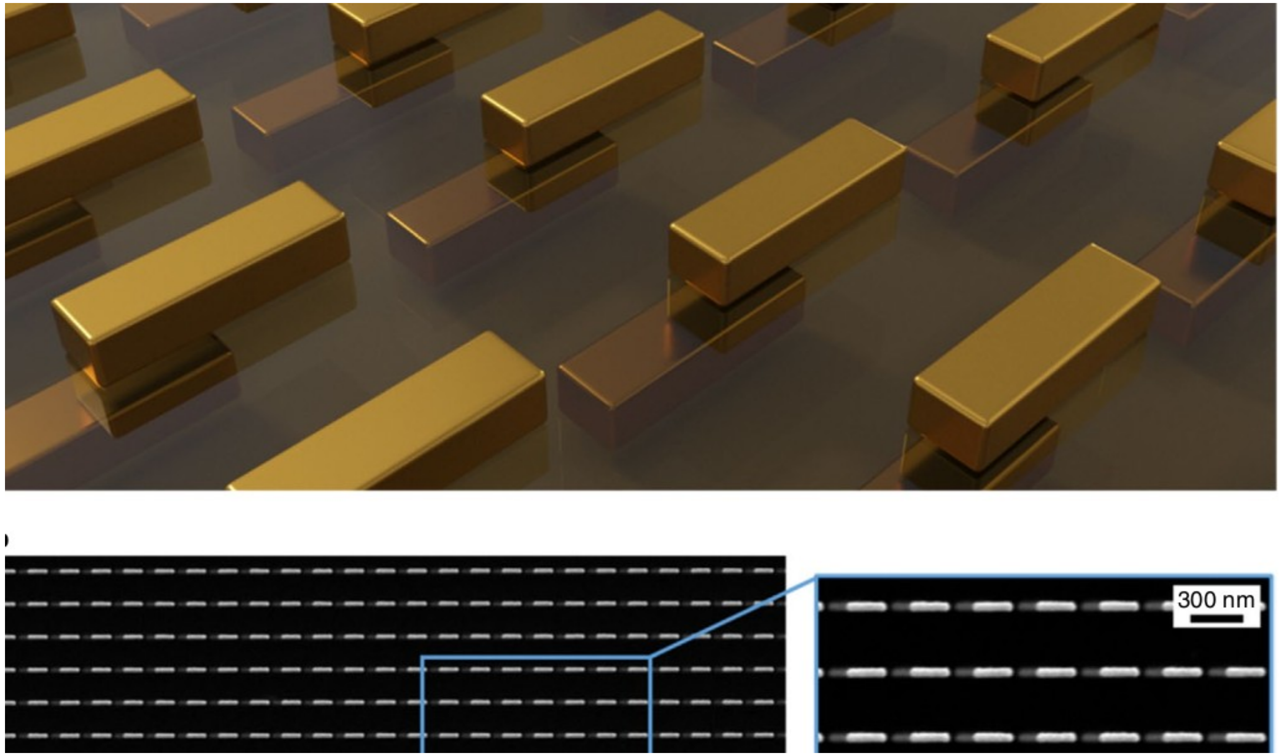
Work supported by FA9550-18-1-0186

- Y. Lee, M. B. On, X. Xiao, and S. J. Ben Yoo, "Demonstration of an Optoelectronic Excitatory & Inhibitory Neuron for Photonic Spiking Neural Networks," in *CLEO 2020*, paper SM1E.6
- M. Nazirzadeh, M. Shamsabardeh, and S. J. Ben Yoo, "Energy-Efficient and High-Throughput Nanophotonic Neuromorphic Computing," in *CLEO 2018*, paper Th3Q.2.
- Yun-Jhu Lee, Mehmet Berkay On, Xian Xiao, Roberto Proietti, and S. J. Ben Yoo, "Photonic spiking neural networks with event-driven femtojoule optoelectronic neurons based on Izhikevich-inspired model," Opt. Express 30, 19360-19389 (2022)



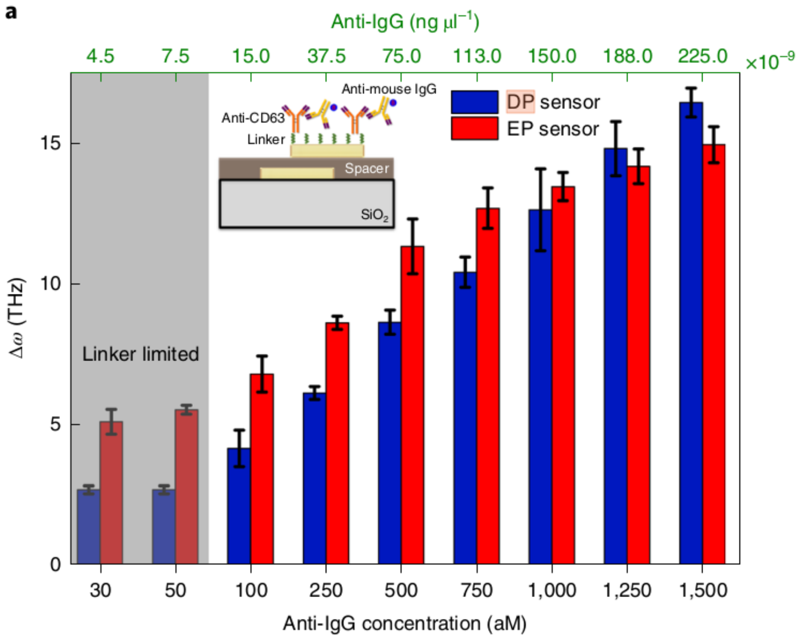
PI Boubacar Kante

Could possibly couple nanoscale hybrids using plasmons

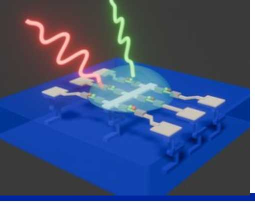


Jun-Hee Park et al, “Symmetry-breaking-induced plasmonic exceptional points and nanoscale sensing”, Nature Physics volume 16, pages462–468 (2020)

Nanoscale patterning used to make sensors based on topological polaritonic effects.

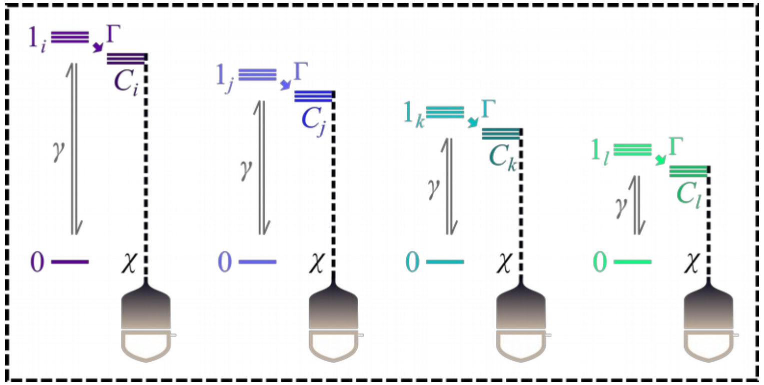


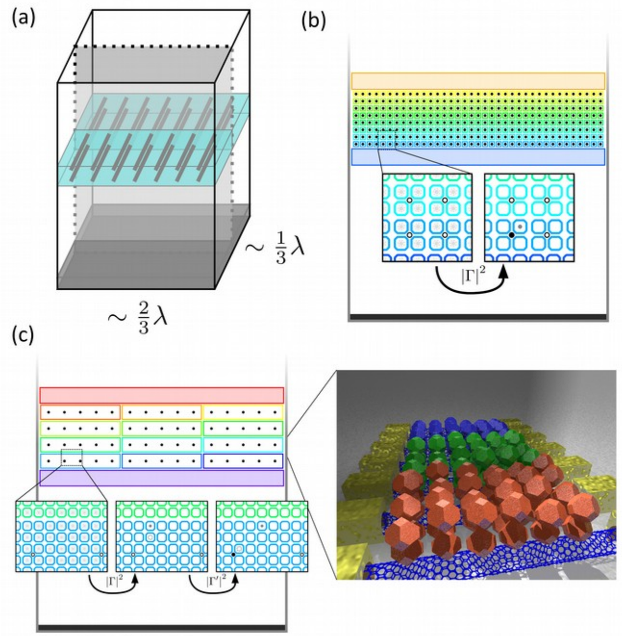
Plasmonic resonance shift dependent on target molecule concentration

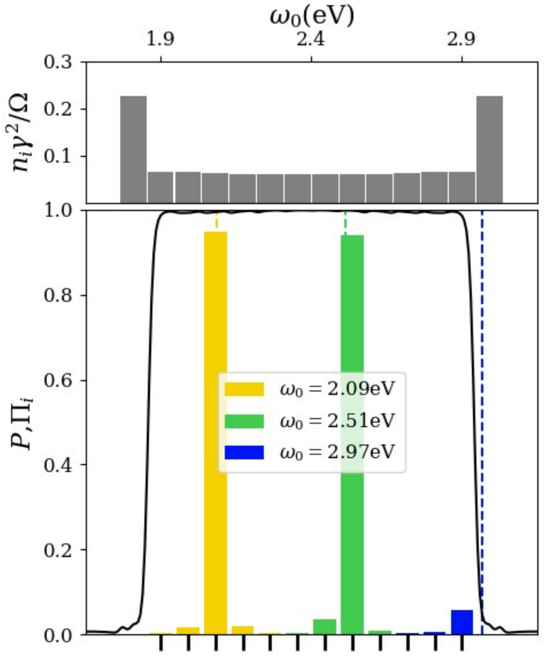


QIS theory is used to calculate the properties of our artificial material for ideal sensing

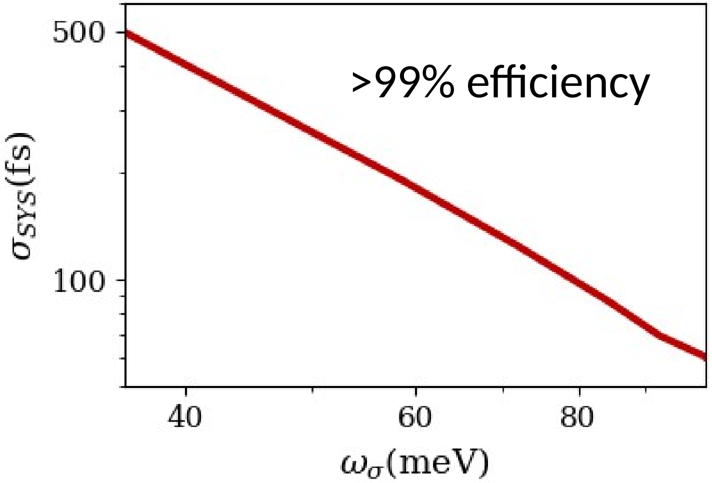
PI François Léonard





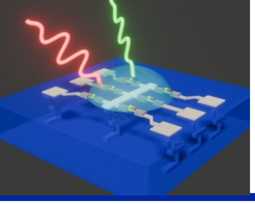


Frequency bins



- -High efficiency
- -Low jitter
- -High frequency resolution

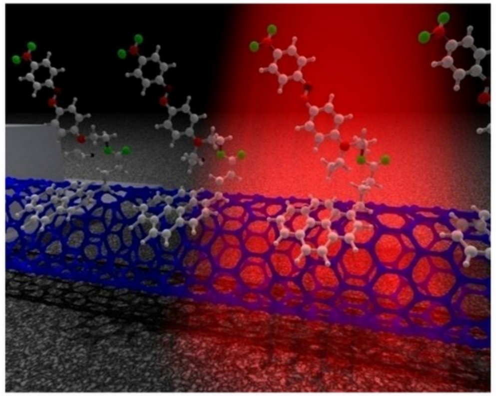
Young, Sarovar, Léonard, *Comm. Phys.* 2023

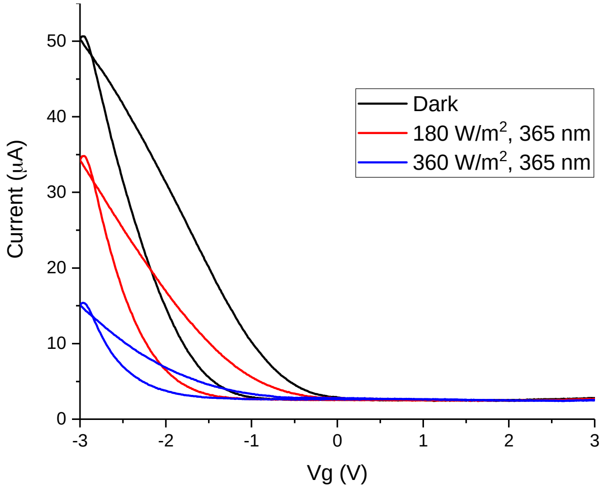


PI François Léonard

Experiments suggest nanoscale hybrids can achieve those properties

Azobenzenes

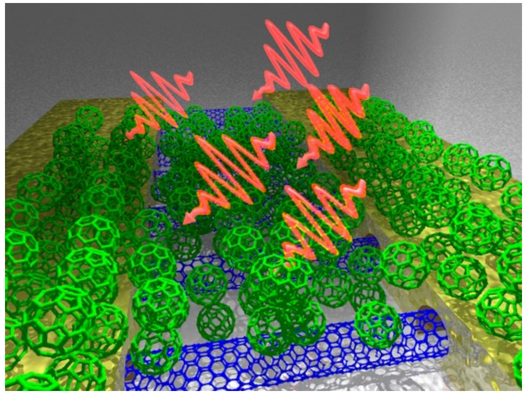


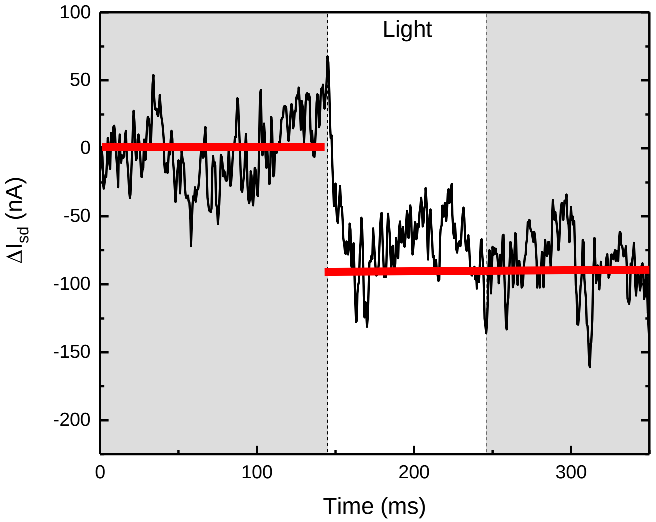


Gain > 10^4 at room temperature

Zhou *et al*, *Nanoletters* (2010)

C_{60}



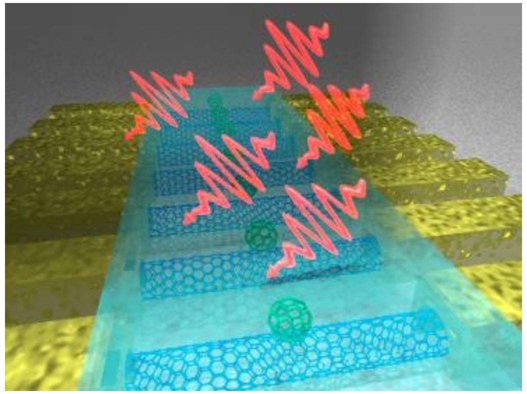


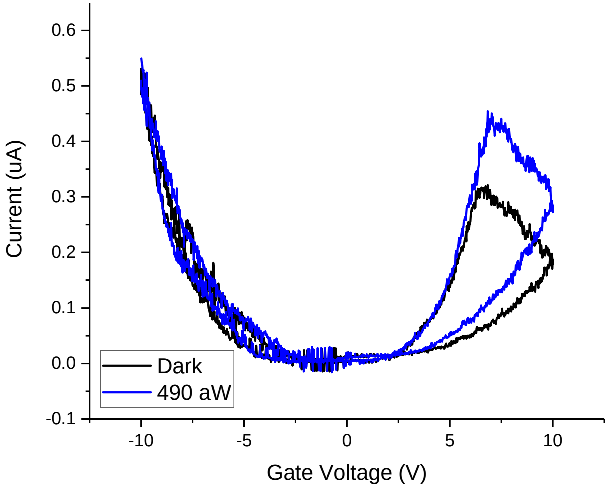
Gain > 10^8 at room temperature

Detection of 200 photons

Bergemann & Léonard, *Small* (2018)

P3HT

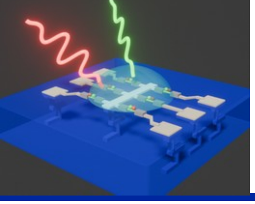




Gain > 10^9 at room temperature

Detection of 8-13 photons/CNT

Bergemann & Léonard, *ACS Nano* (2021)

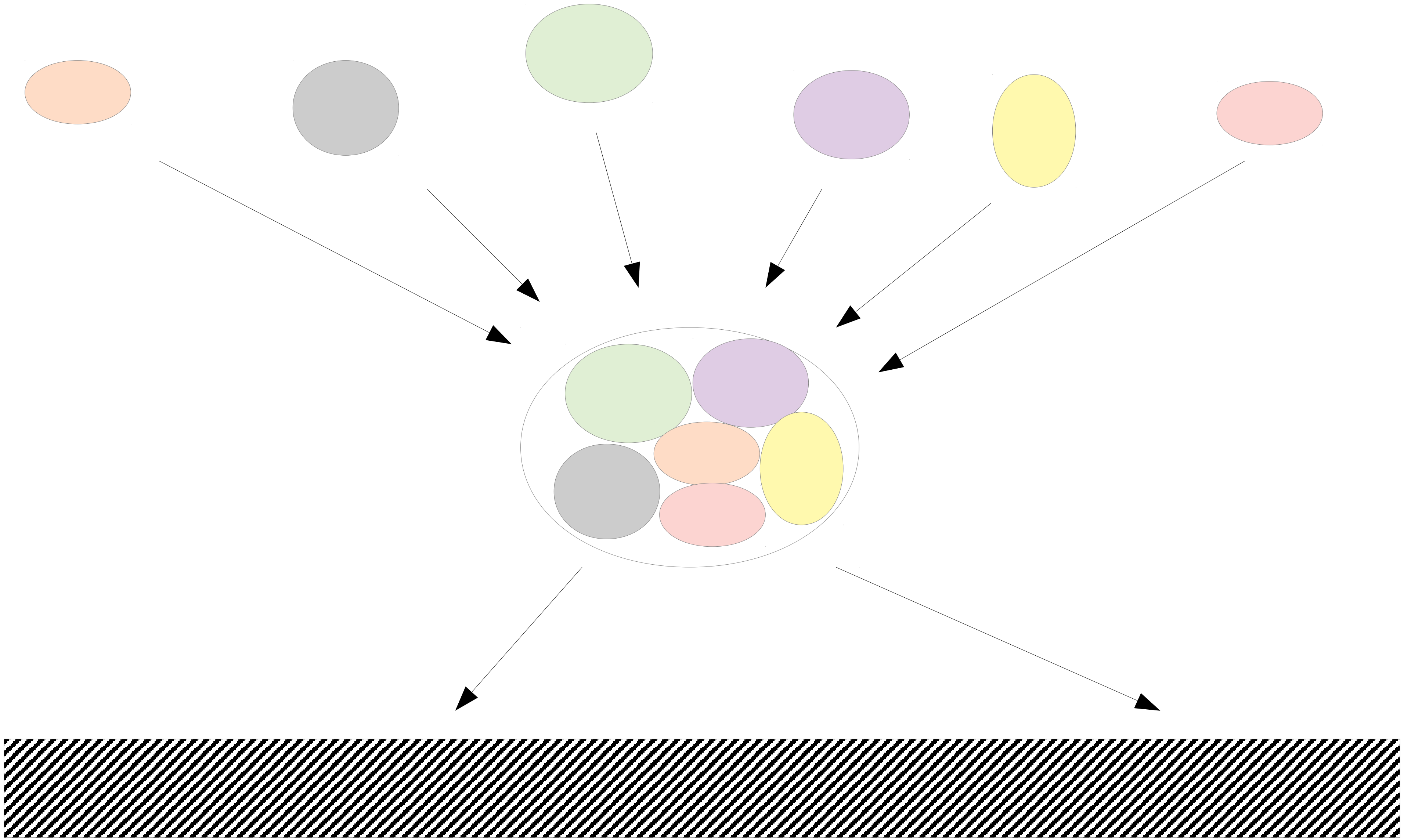


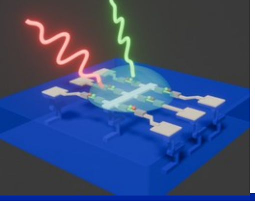
Modeling

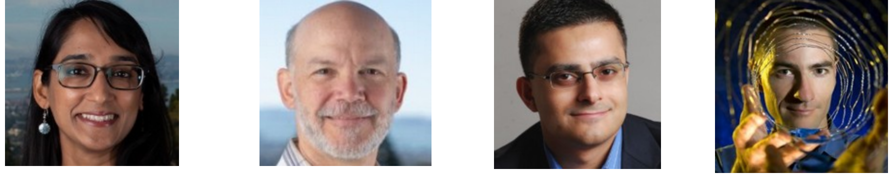
PIs Andy Nonaka, Jackie Yao

- See later slides by Jackie Yao
- Modeling tools could be of fairly wide interest within MEERCAT so decided to highlight this aspect.

Development of ingredients & assembly



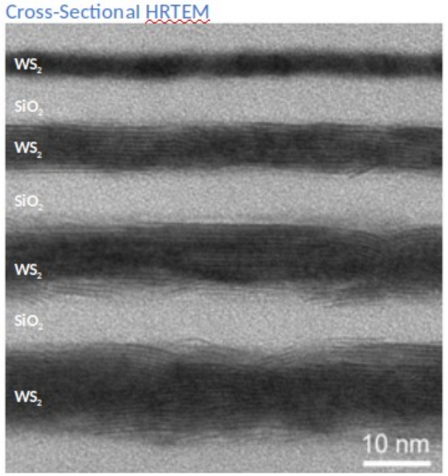




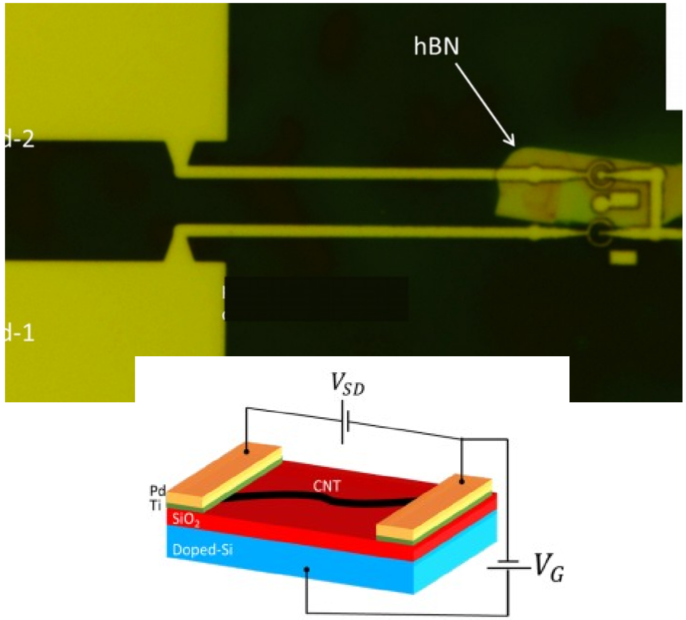
Archna Raja, Tev Kuykendal, Ali Javey, François Léonard

1D and 2D Materials

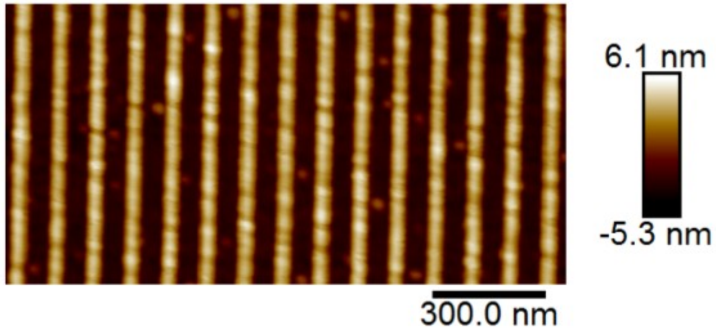
Lithographically defined TMD alloys and heterostructures



CNTs on HBN flakes

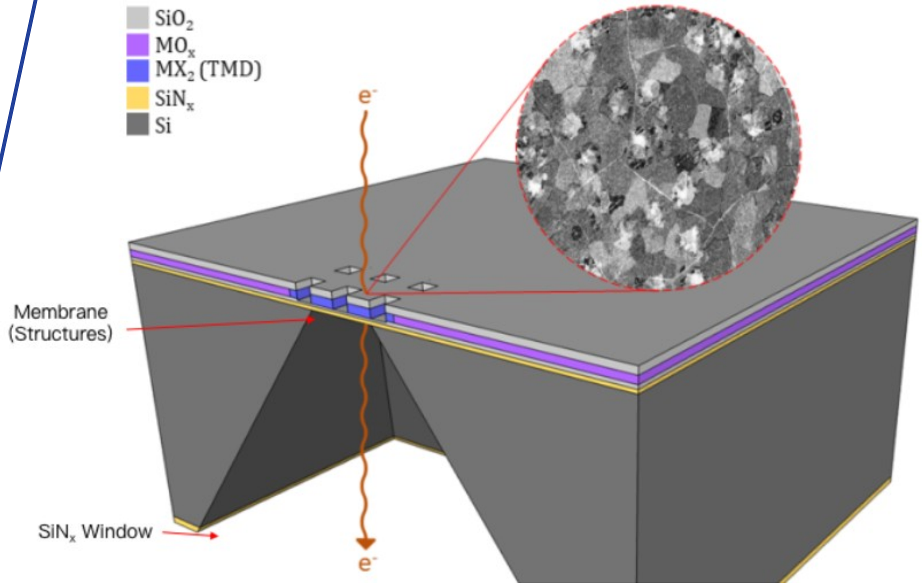


Te Nanowires

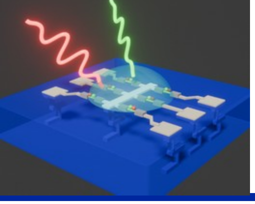


Extensive characterization capabilities and expertise. Just one example:

Fabrication & Design SiNx Membranes for TMD lateral conversion and TEM analysis

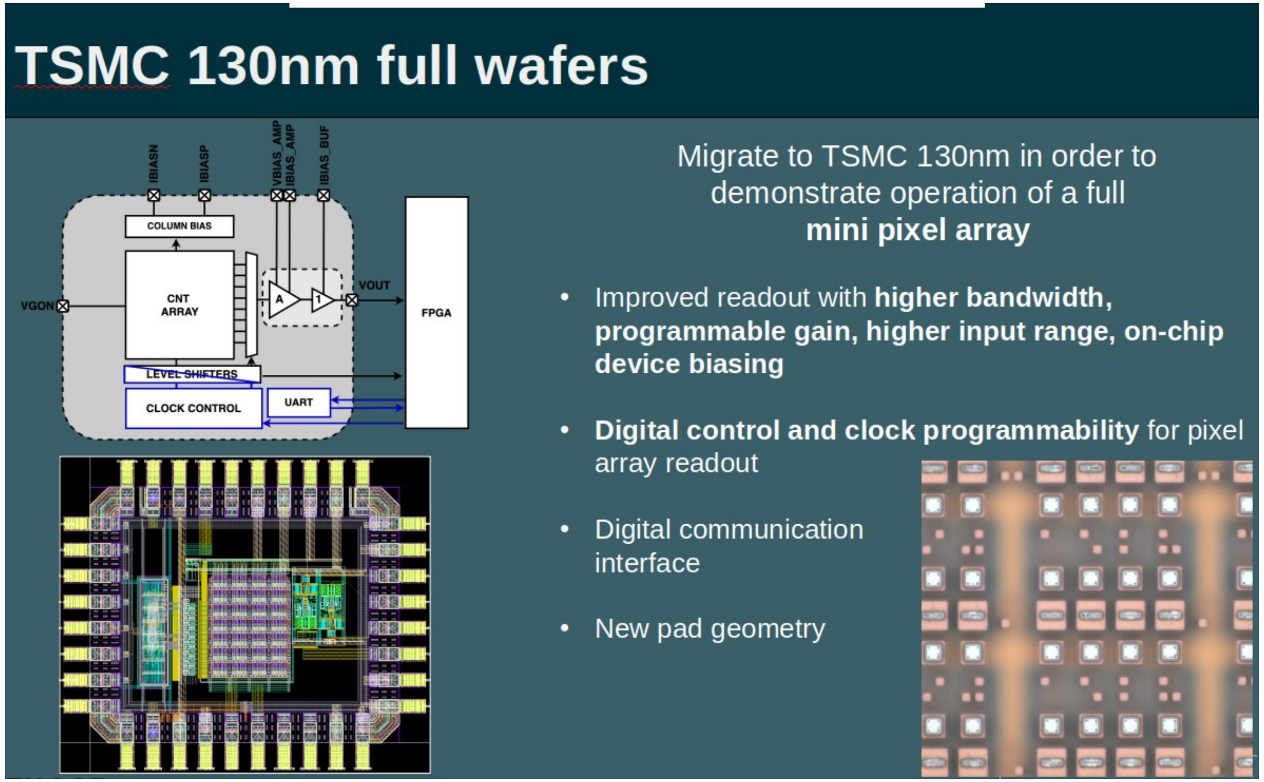


https://foundry.lbl.gov/expertise-instrumentation/#characterization-instrumentation



CMOS substrates

PIs Katerina Papadopoulou, Yuan Mei



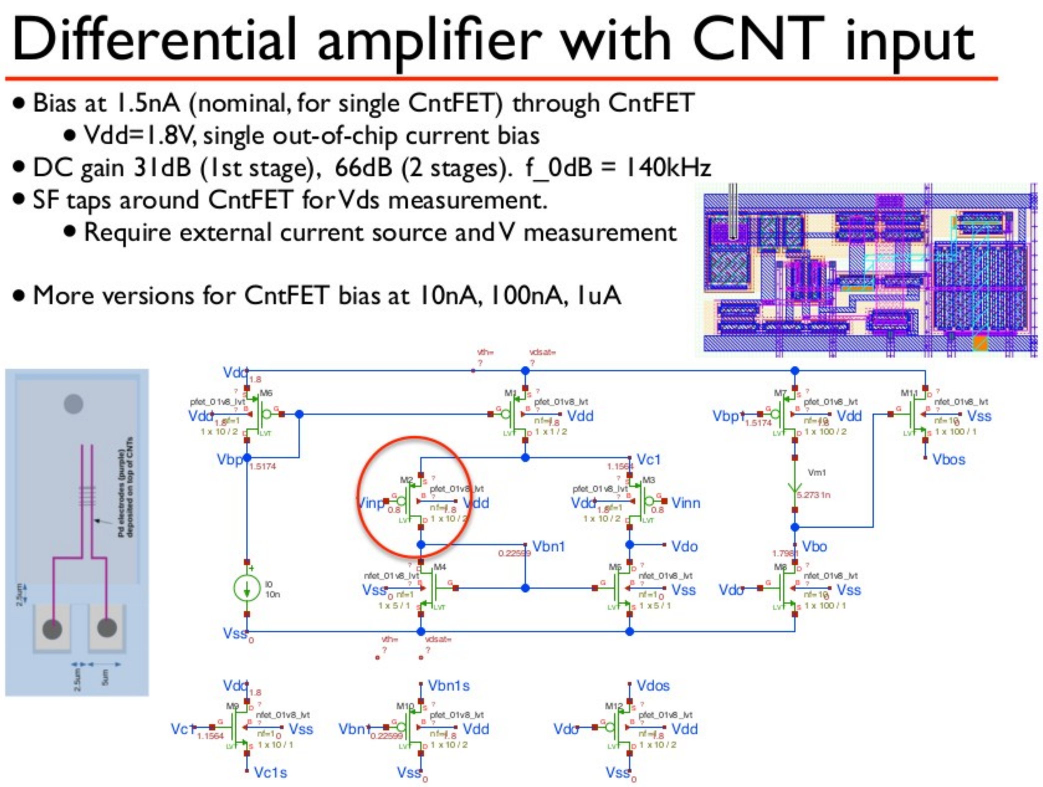
TSMC 130nm full wafers

Migrate to TSMC 130nm in order to demonstrate operation of a full **mini pixel array**

- Improved readout with **higher bandwidth, programmable gain, higher input range, on-chip device biasing**
- **Digital control and clock programmability** for pixel array readout
- Digital communication interface
- New pad geometry

6. SkyWater 130nm full wafers

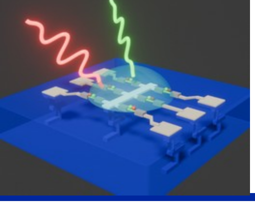
NIST + Google + skywater Nanotechnology Accelerator Program



Differential amplifier with CNT input

- Bias at 1.5nA (nominal, for single CntFET) through CntFET
  - Vdd=1.8V, single out-of-chip current bias
- DC gain 31dB (1st stage), 66dB (2 stages). f_0dB = 140kHz
- SF taps around CntFET for Vds measurement.
  - Require external current source and V measurement
- More versions for CntFET bias at 10nA, 100nA, 1uA

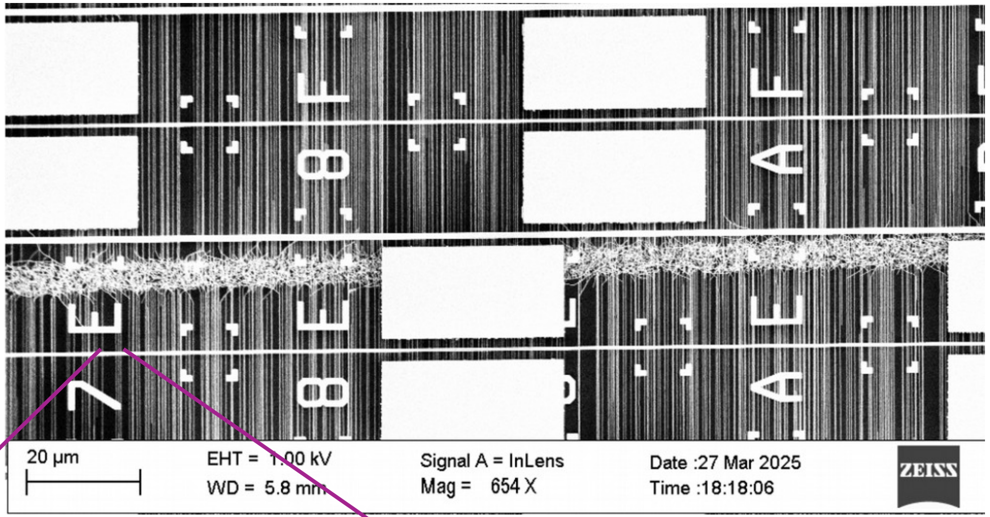
Now starting design for 40nm TSMC through DOD Microlectronics Commons project

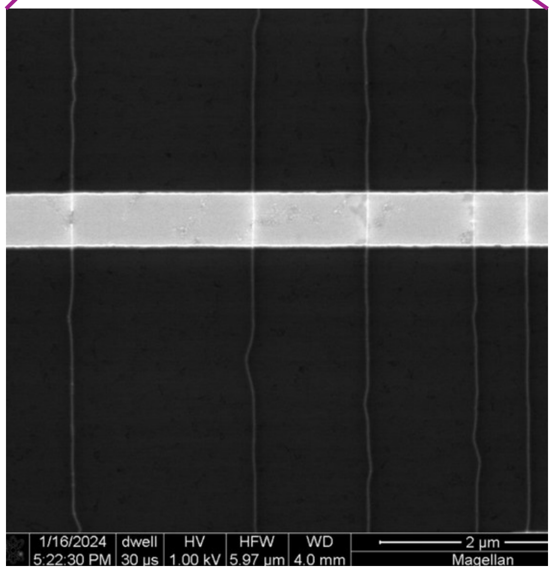


Patterning and imaging

PIs Mi-Young Im, Weilun Chao

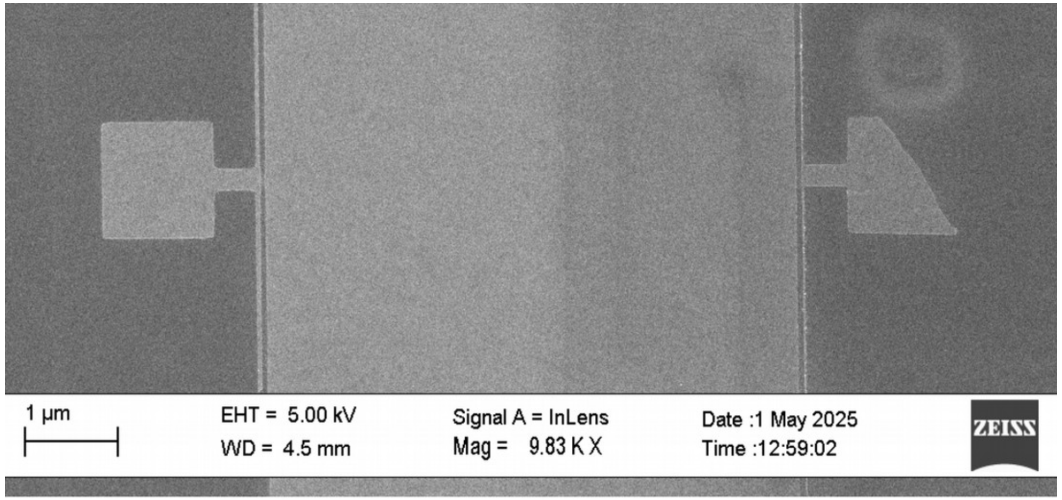
Patterned trenches and contacts on CNTs

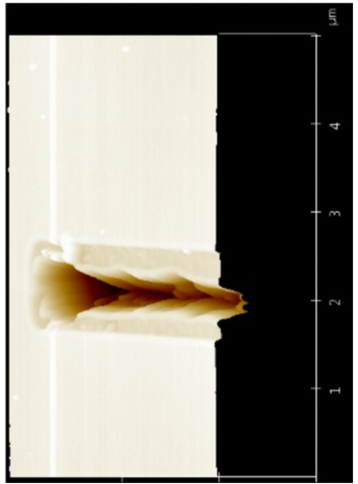




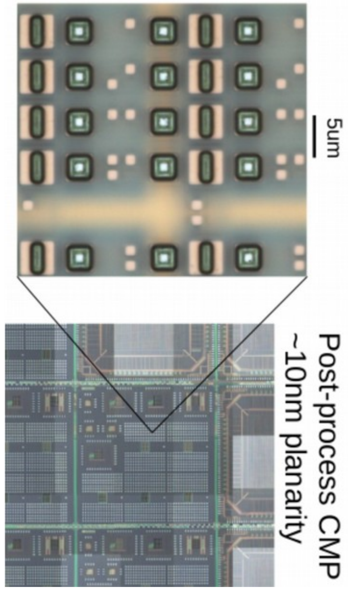
CNTs bridging 1um wide trench

Patterned Te nanowires



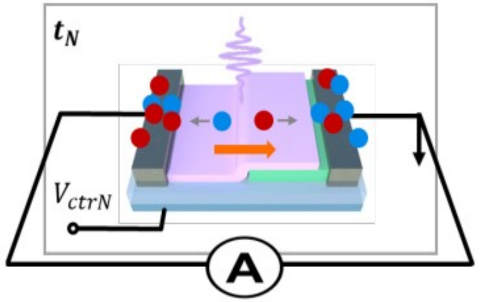


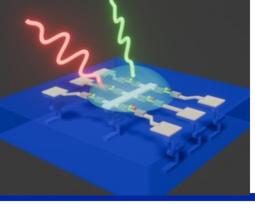
AFM of trench on CMOS chip



Post-process CMP ~10nm planarity

Work to build demonstrator to replicate spectroscopic functionality with nanohybrids

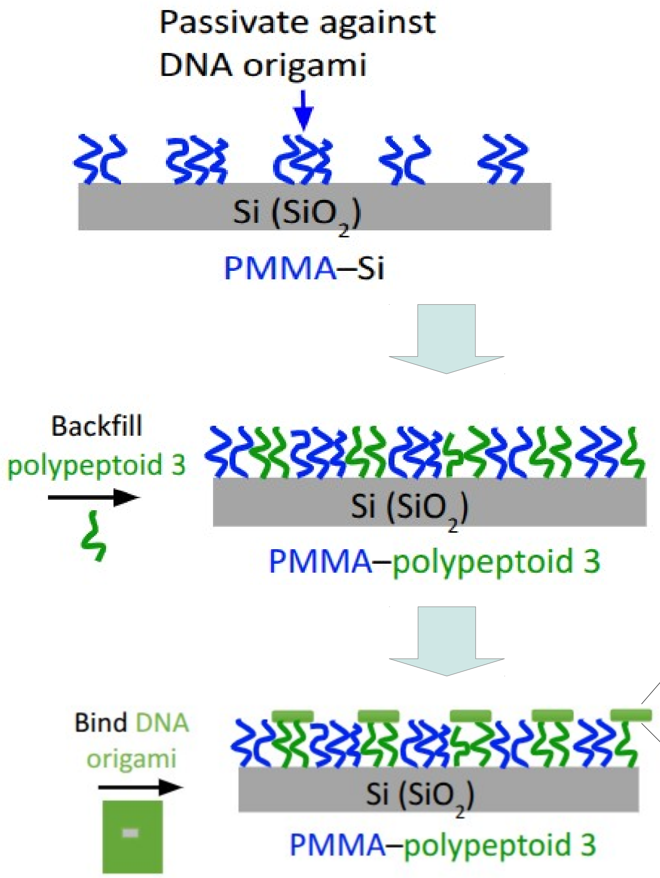




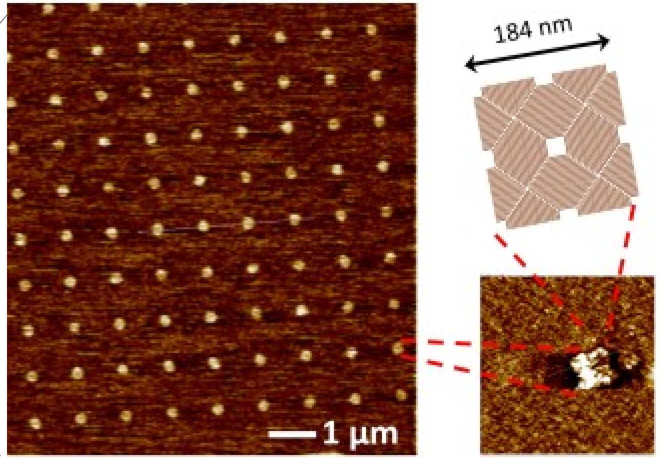
Directed Self-Assembly

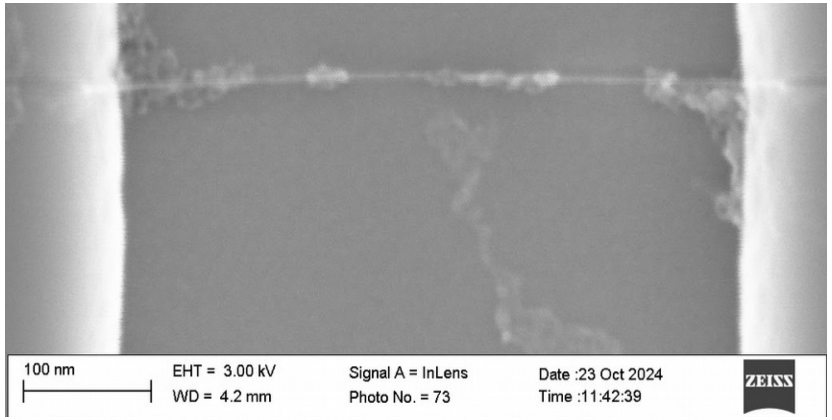
PIs Ricardo Ruiz, Greg Tikhomirov

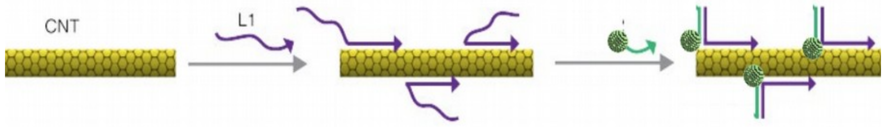
Polypeptoid brush patterning

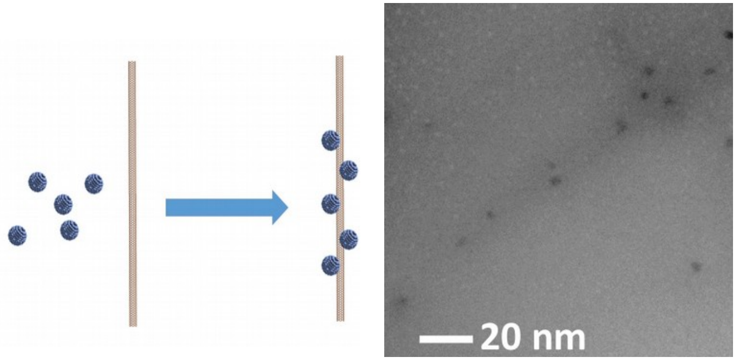


DNA origami breadboards attached to pattern-defined sites
Each breadboard could eventually be a nanohybrid





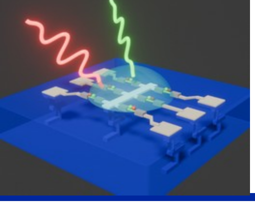




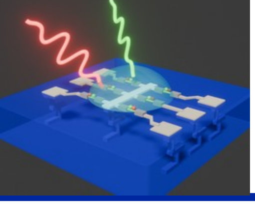
B. Yu, R. Ruiz et al. ACS Nano, 2024, 18, 7411-7423.

Yunjeong Park and Grigory Tikhomirov "Nanometer-precise DSA with DNA", Proc. SPIE 13427, Novel Patterning Technologies 2025, 134270M (2025)

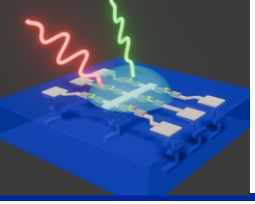
Durham Smith and Grigory Tikhomirov ACS Applied Optical Materials 2025 3 (3), 569-574



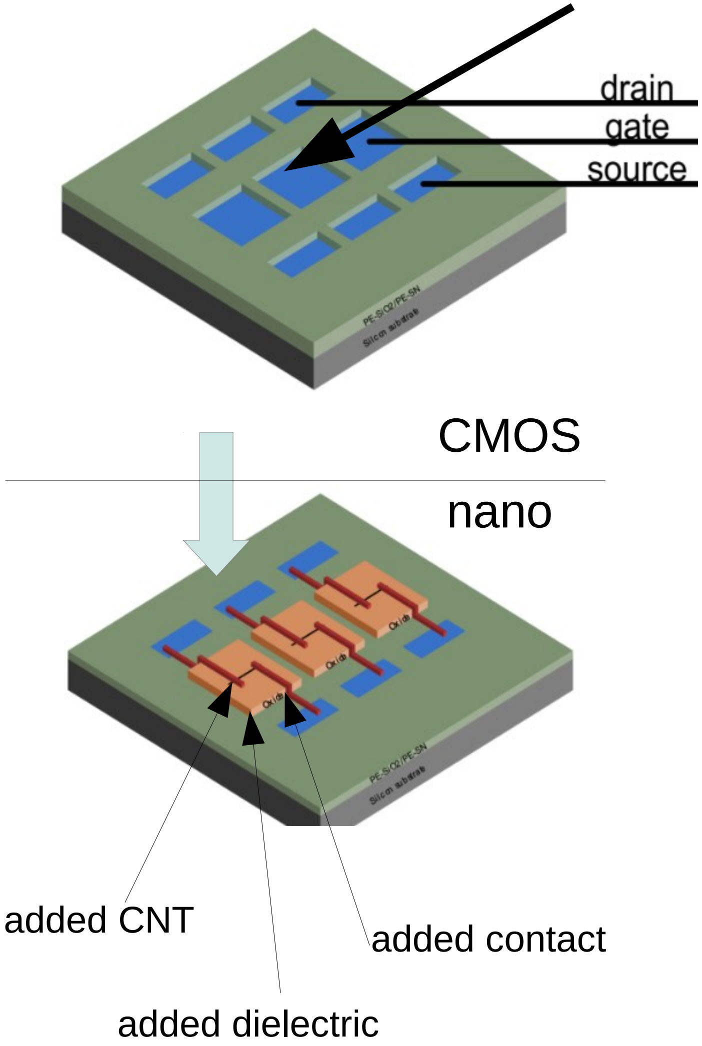
Over to Jackie

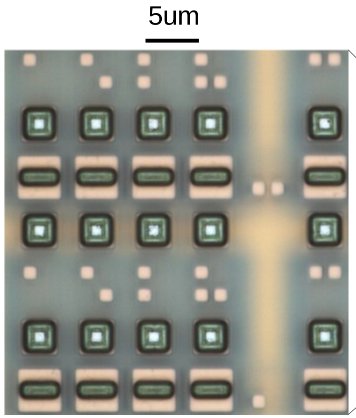


BACKUP



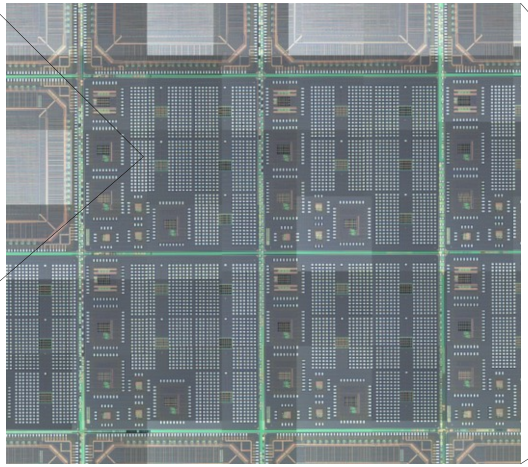
CMOS integration work- standard wafers

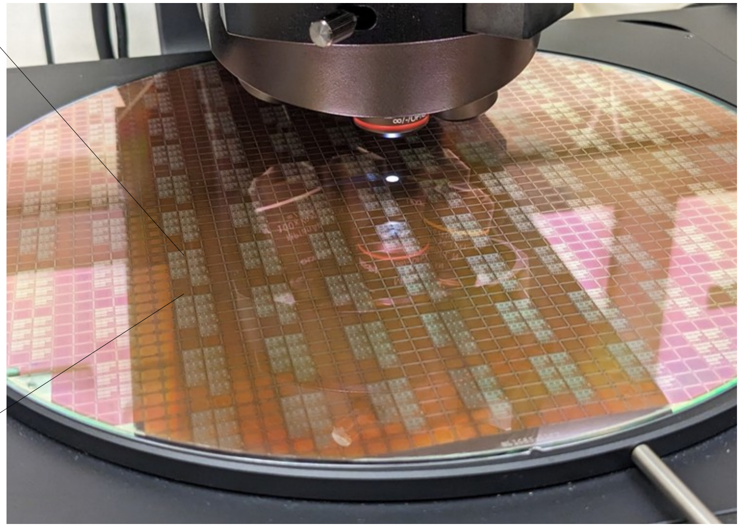




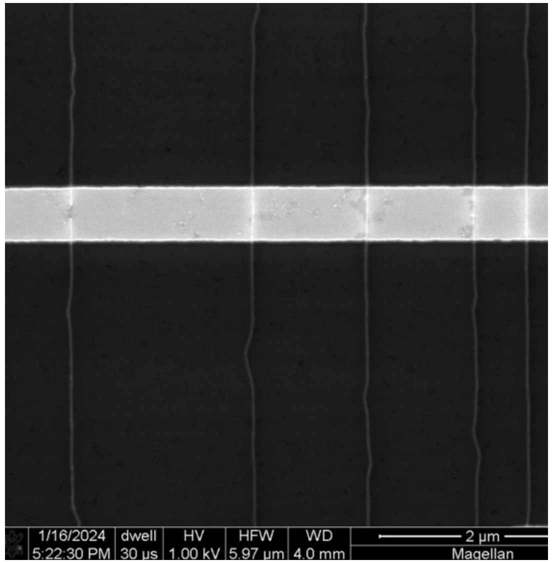
Long parallel CNTs Bridging a trench like this one

Post-process CMP on finished wafers
~10nm planarity

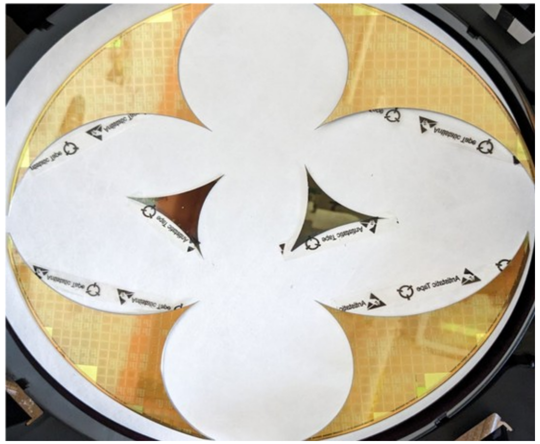




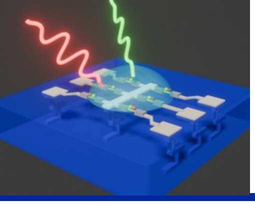
130nm wafer run shared w/LArPix



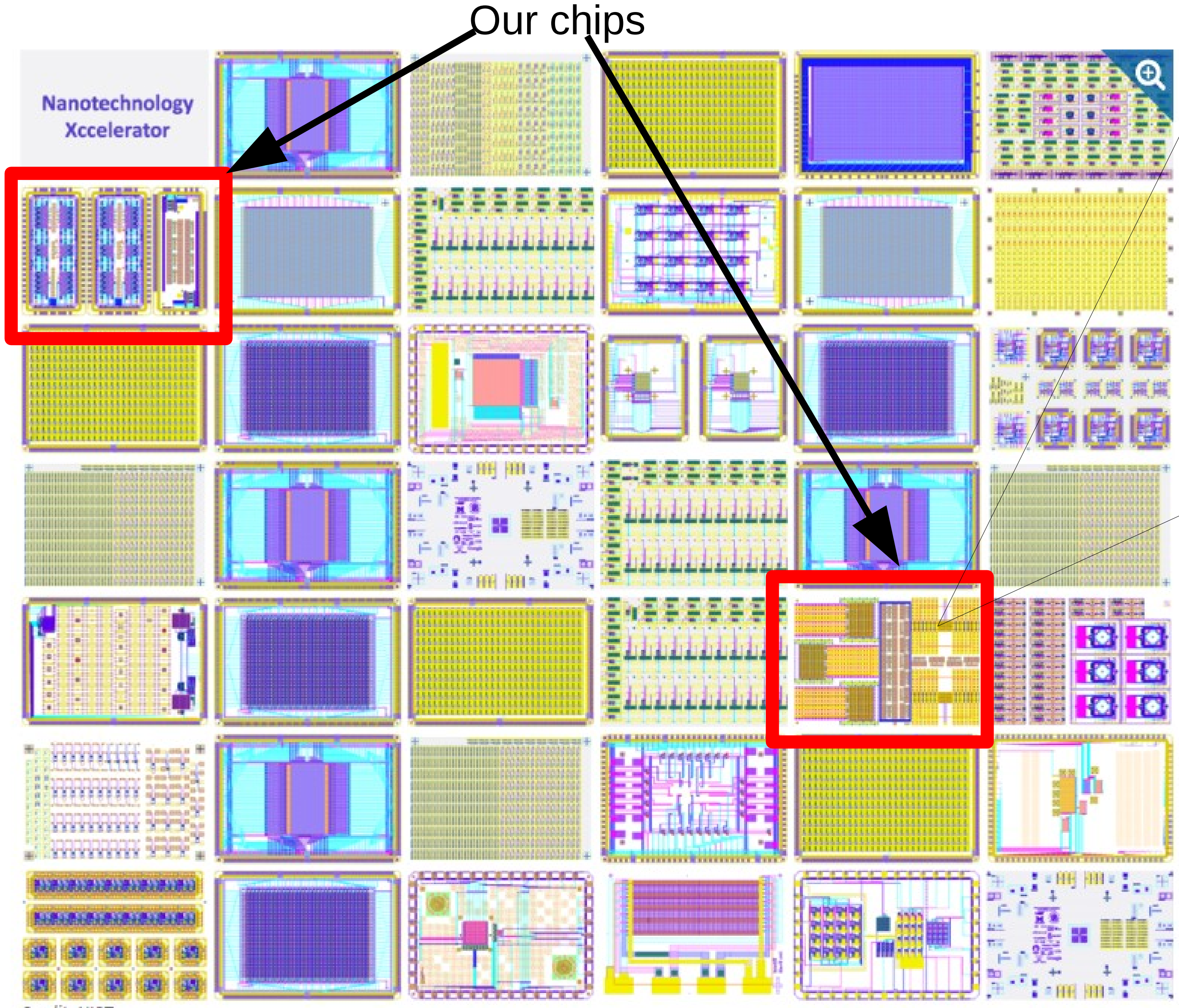
Courtesy of Aligned Carbon, Inc.



Wafer cored and polished



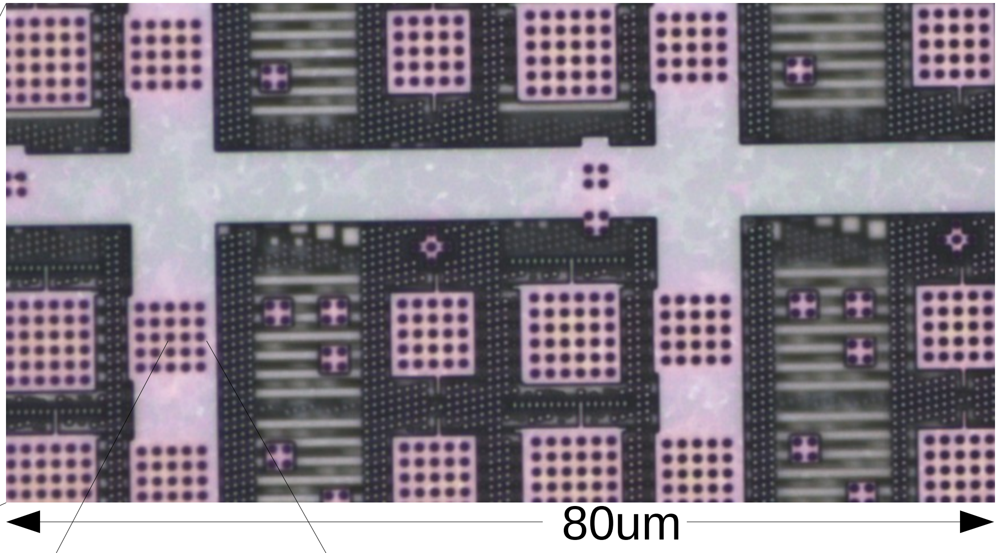
NIST Nanotechnology Xcelerator Wafers



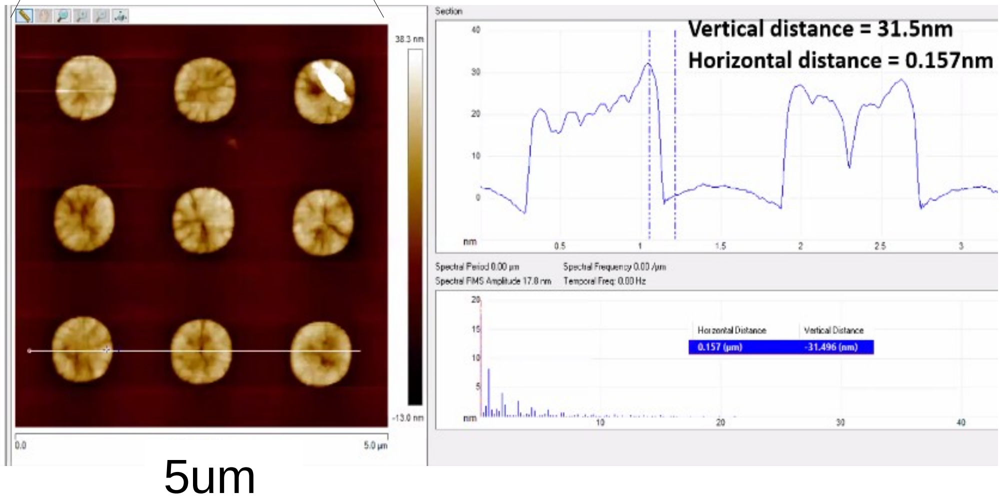
Credit: NIST

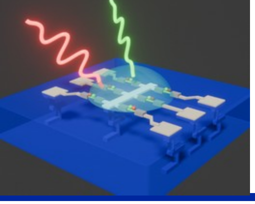
https://www.nist.gov/programs-projects/nanotechnology-xccelerator

optical

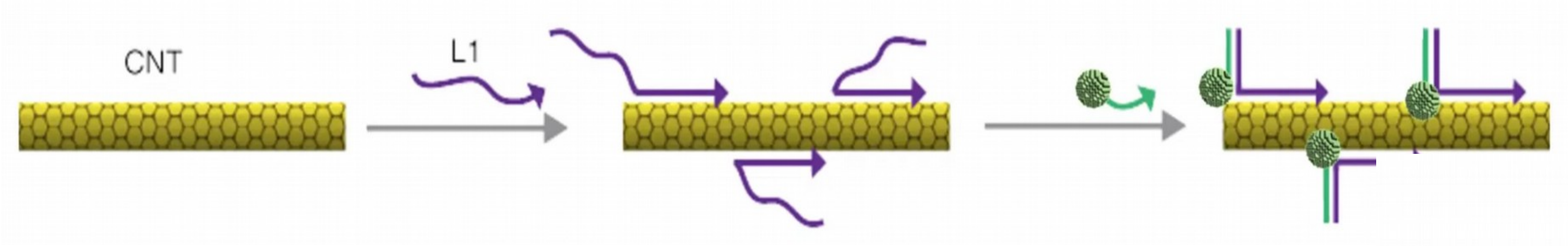


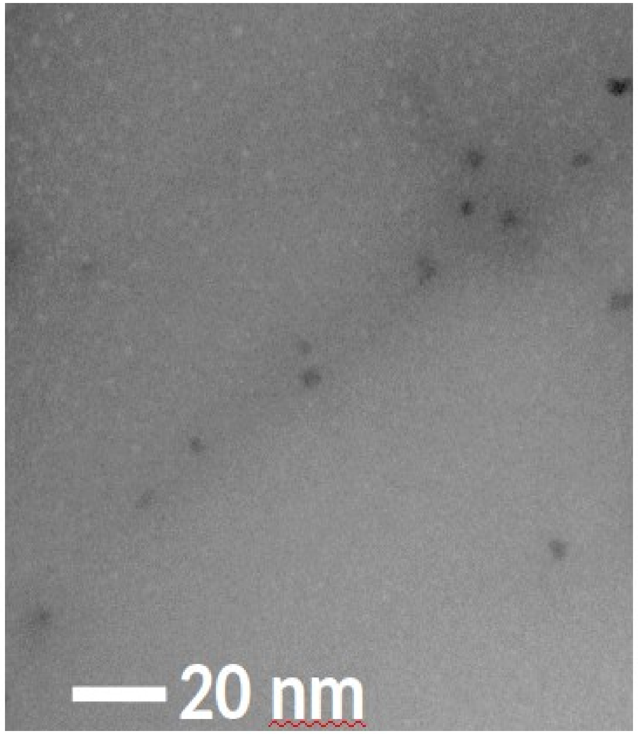
AFM

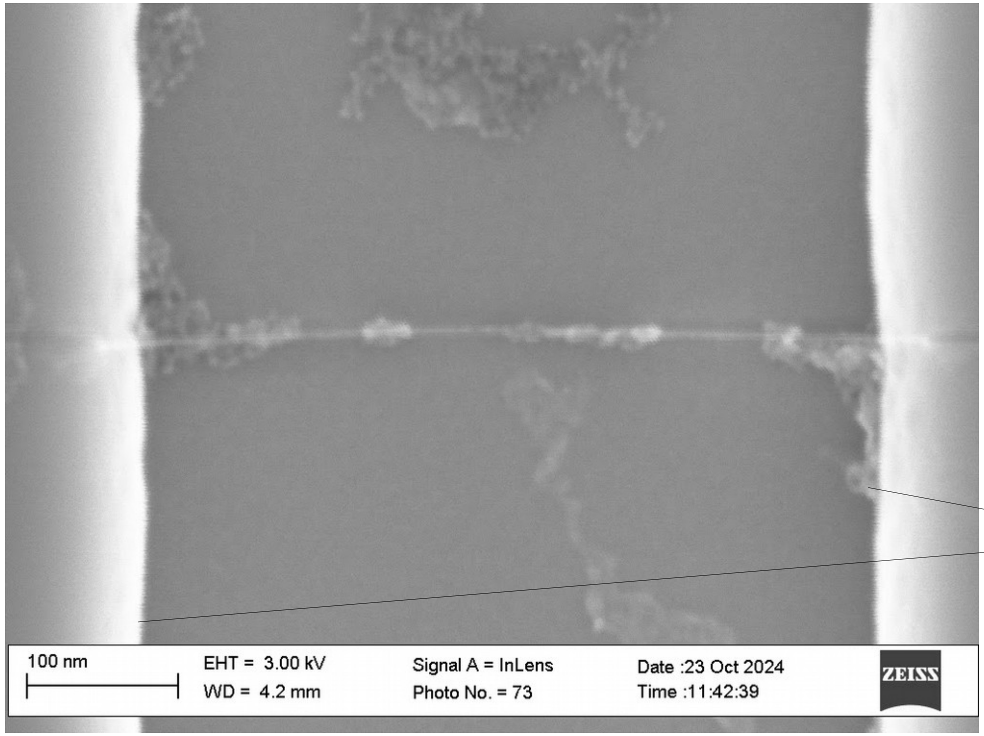


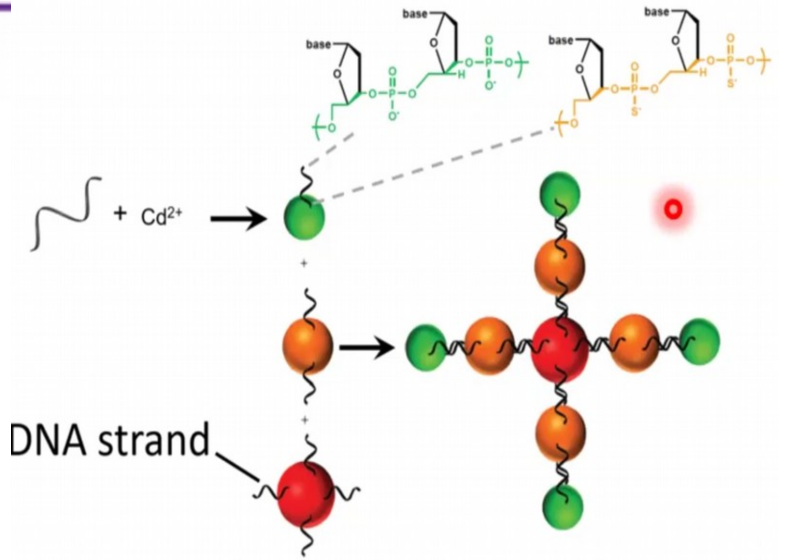


Added QDs using DNA self-assembly

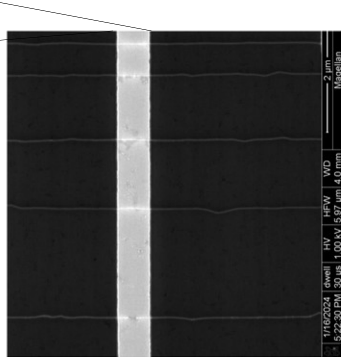




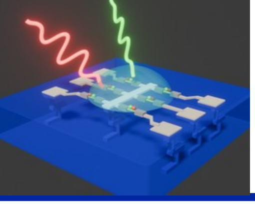




Tikhomirov et al, Nature Nanotechnology 2011

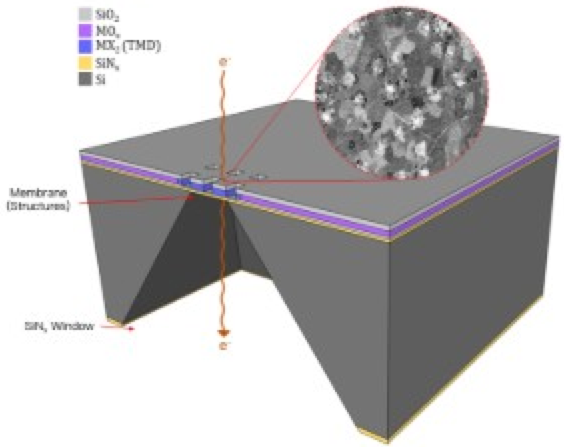


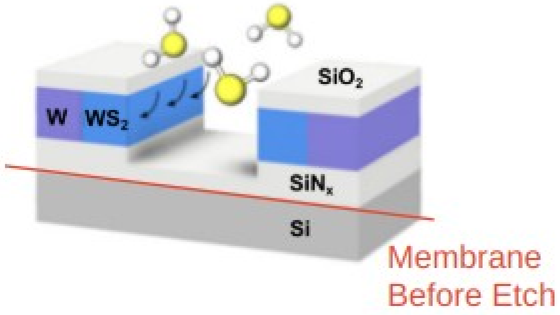
TEM and AFM of quantum dots attached to CNTs



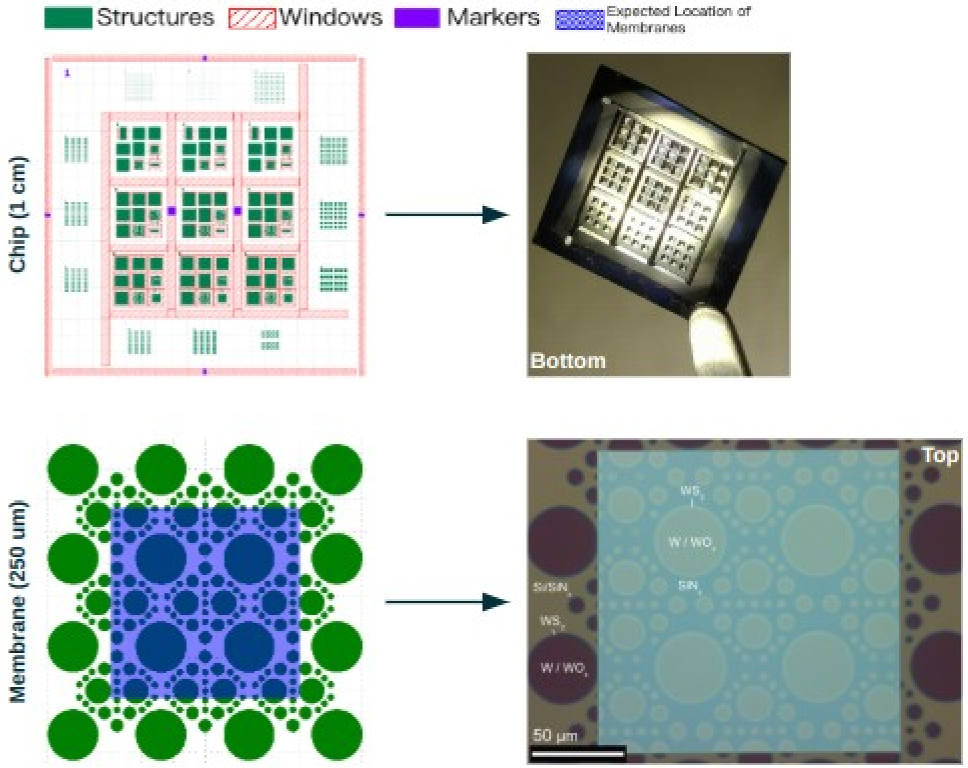
Integrated SiNx Membranes for TEM: Lateral Conversion

A. SiN_x Membranes Model

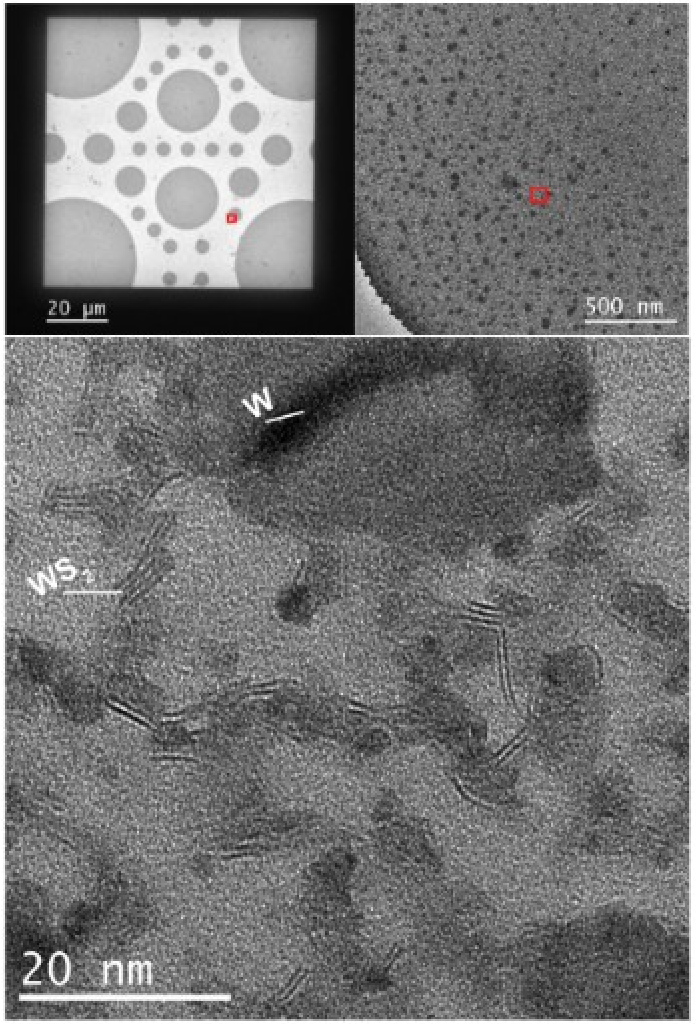


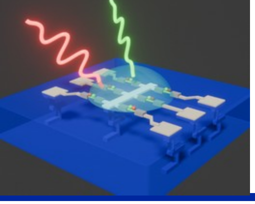


B. Shadow Mask Design & Results

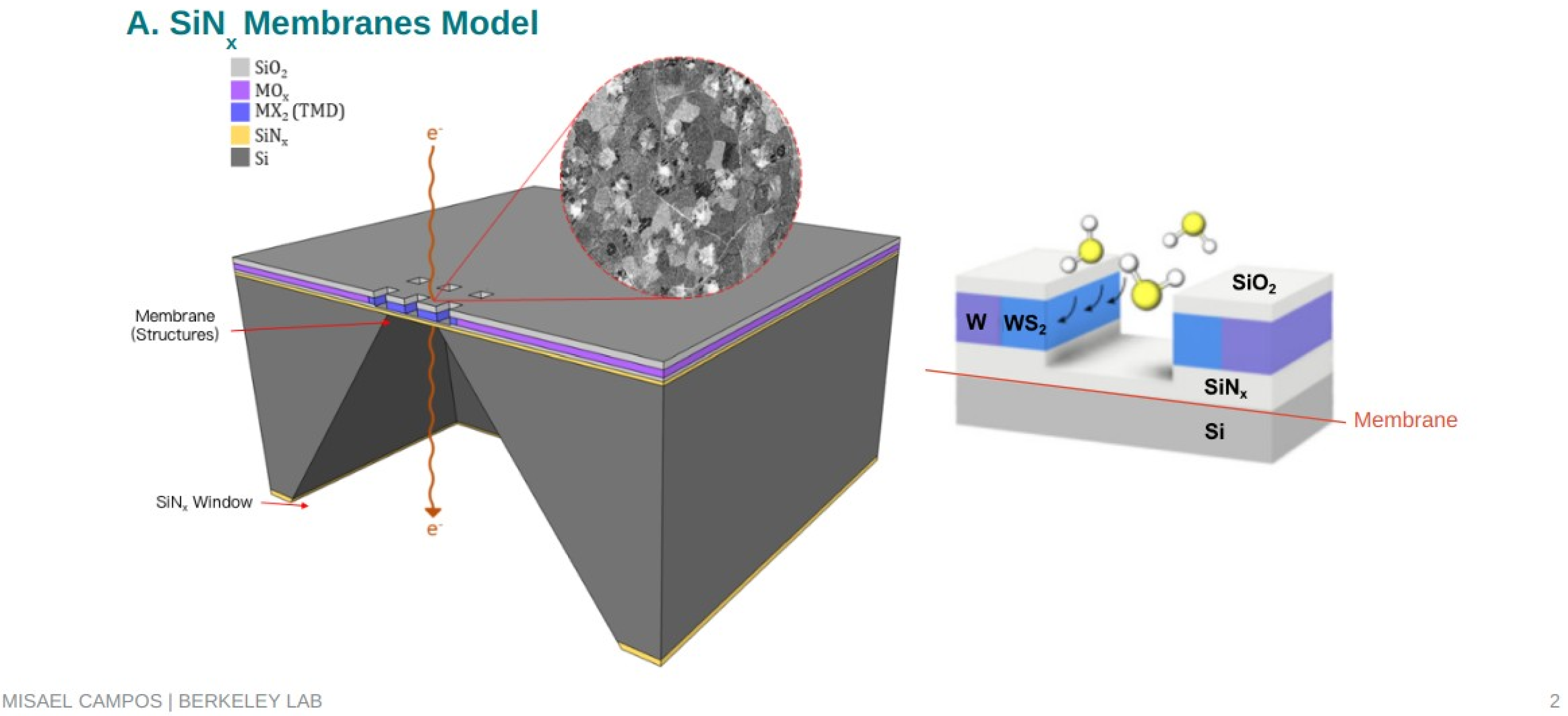


C. TEM (Partially Converted Area)





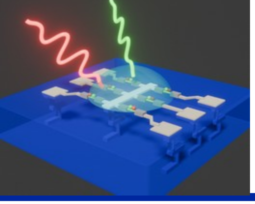
Integrated SiNx Membranes for Transmission Electron Microscopy



A. SiN_x Membranes Model

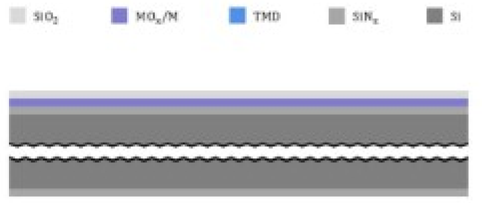
MISAEL CAMPOS | BERKELEY LAB

2

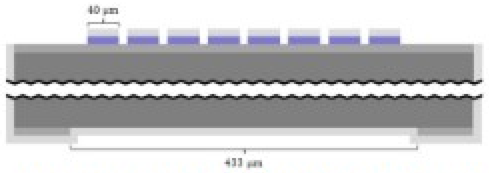


Fabrication & Design SiNx Membranes for TEM

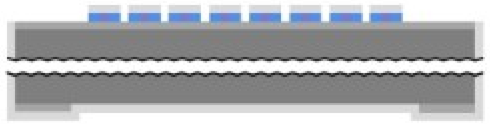
A. Fabrication Process



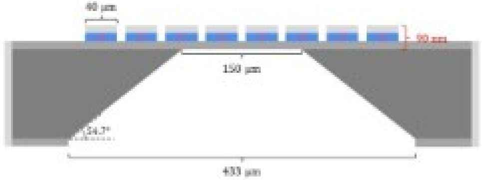
1. Deposition



2. Patterning (Photolithography)

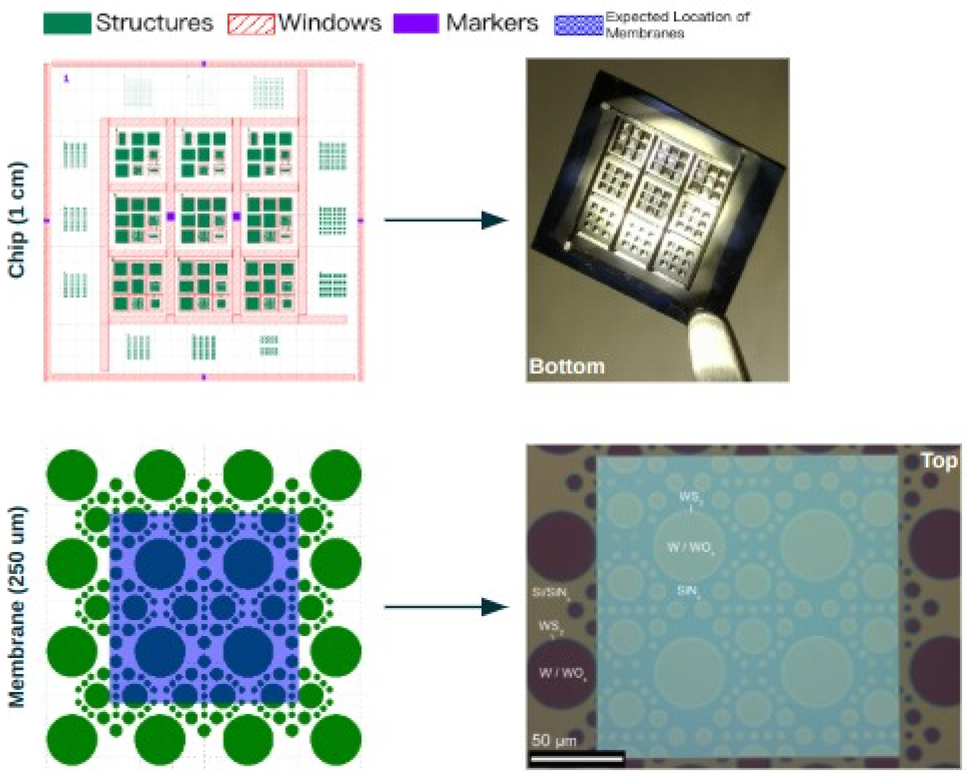


3. Lateral Conversion

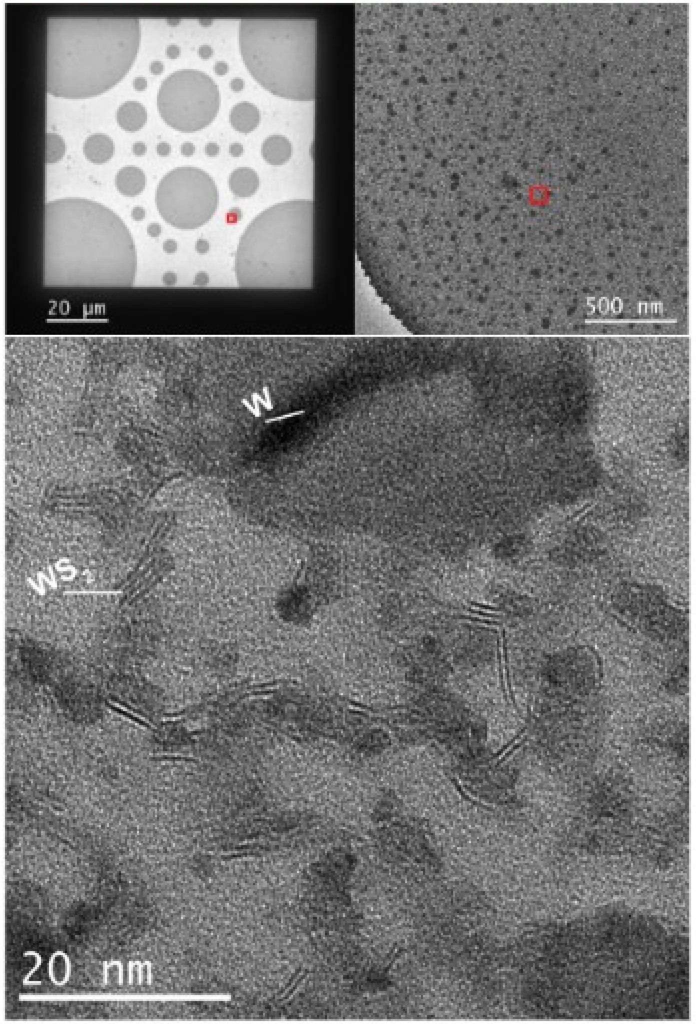


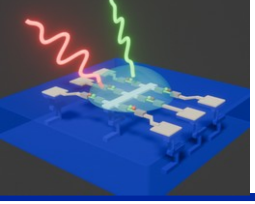
4. Membrane Etch (KOH)

B. Shadow Mask Design & Results



C. TEM (Partially Converted Area)





Consider silicon