



Nanoscale Photon Sensing

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Lawrence Berkeley National Lab

CPAD Workshop, Nov. 21, 2024

Multi-disciplinary project

Engineering

IC Design & Microfabrication

Center for X-Ray Optics

Nanotechnology

UC Berkeley Electrical Engineering

Physics

Theory & Simulation

Computational Research

Molecular Foundry

Sandia National Lab Nanoelectronics and Nanophotonics

BERKELEY LAB

Perlmutter

photon
electron
Molecular film

PI
CNT
SiO₂
Gate

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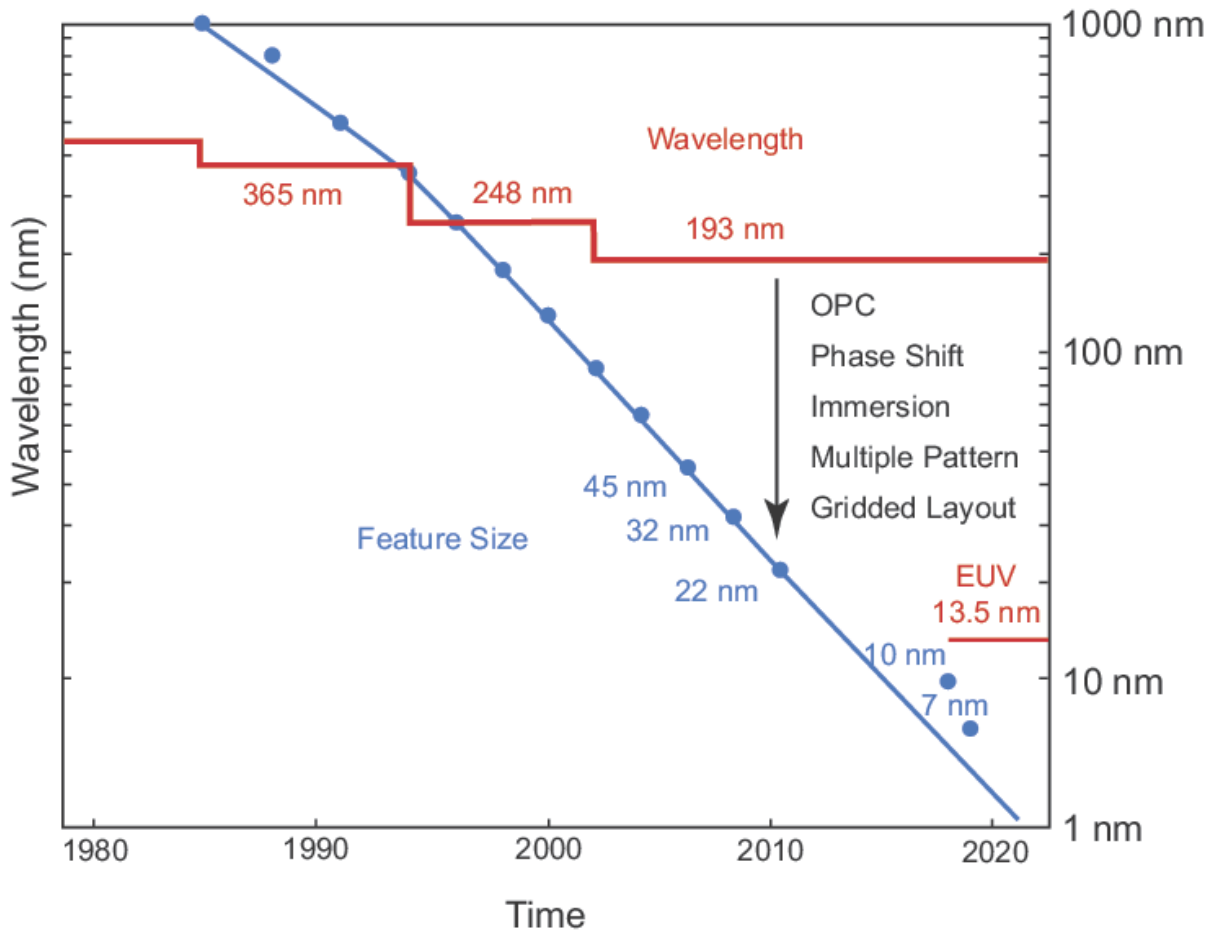
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Historical progression of IC feature size and photolithography technologies from Newport web site

nature nanotechnology

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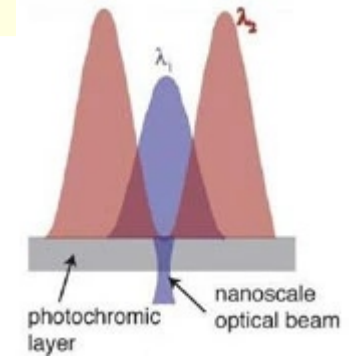
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Research Highlights | Published: 24 April 2009

Nanopatterning

What diffraction limit?

Peter Rodgers



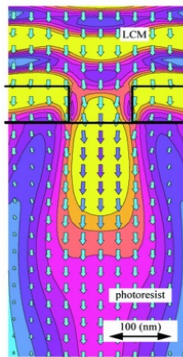
Optics Express Vol. 3, Issue 7, pp. 280-285 (1998) • <https://doi.org/10.1364/OE.3.000280>



Energy flow in light-coupling masks for lensless optical lithography

Olivier J. F. Martin, Nicolas B. Piller, Heinz Schmid, Hans Biebuyck, and Bruno Michel

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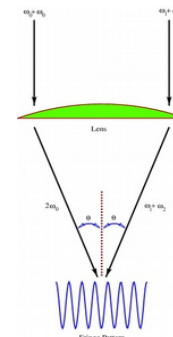
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Rabi Oscillations

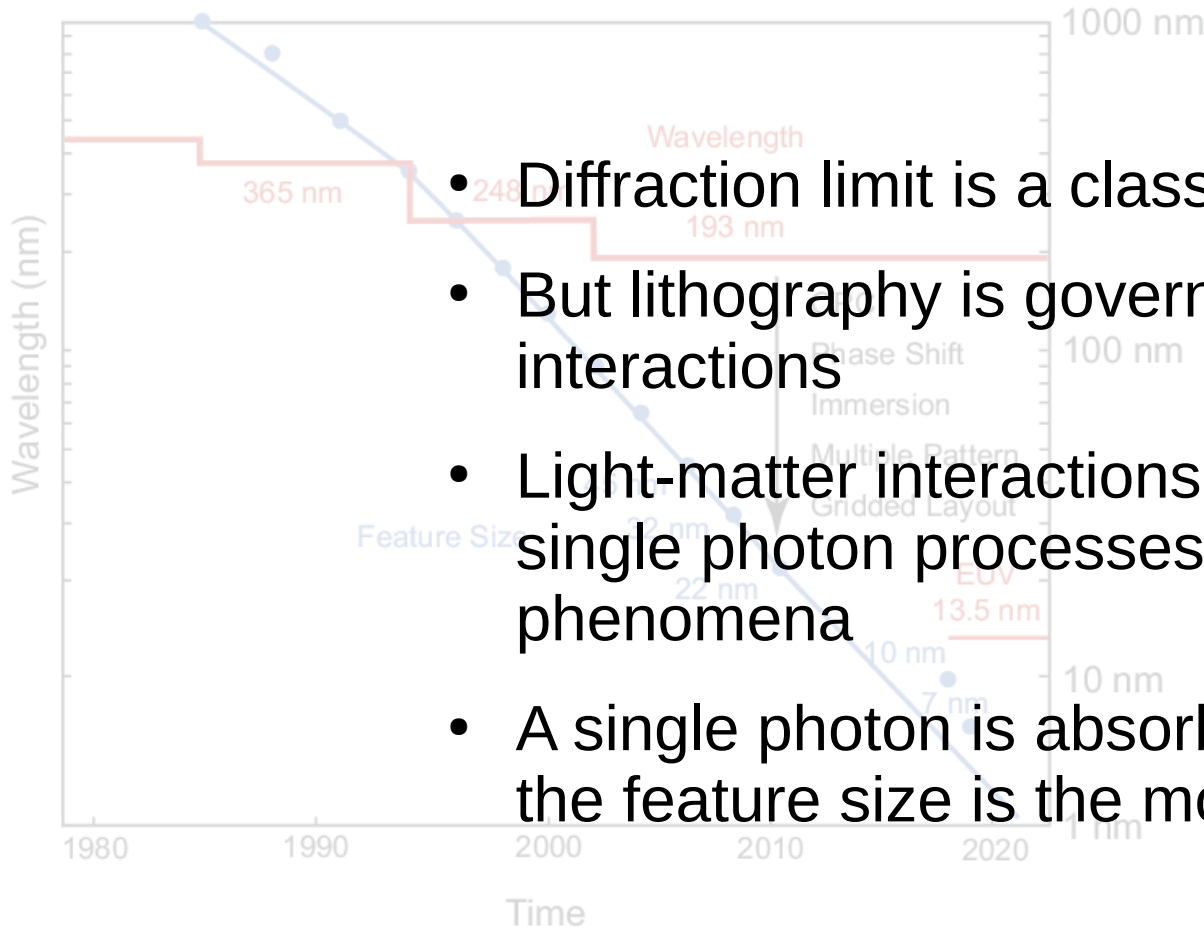
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Beyond the Rayleigh Limit in Optical Lithography

M. Suhail Zubairy



What Diffraction Limit?



- Diffraction limit is a classical wave phenomenon
- But lithography is governed by light-matter interactions
- Light-matter interactions are quantum mechanical, single photon processes, not classical wave phenomena
- A single photon is absorbed by a single molecule- the feature size is the molecule, not the wavelength

nature nanotechnology multi-photon

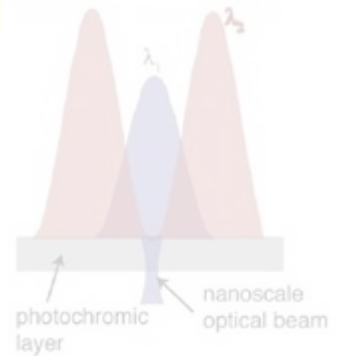
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Nanopatterning

What diffraction limit?

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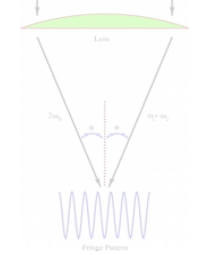
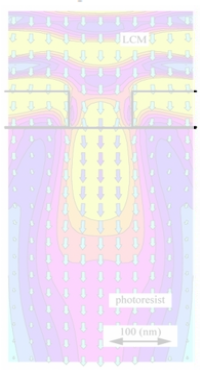
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lithography

Olivier J. F. Martin, Nicolas B. Piller, Heinz Schmid, Hans Biebuyck, and Bruno Michel

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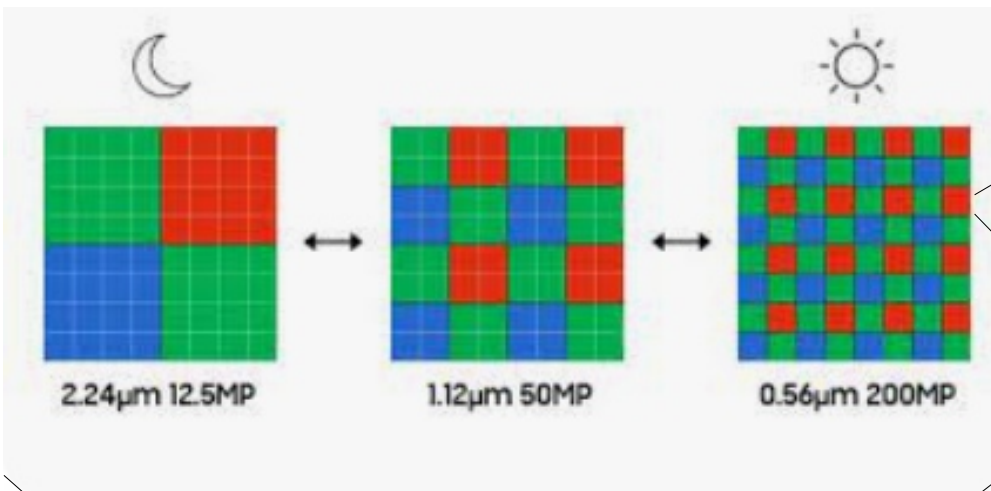
Beyond the Rayleigh Limit in Optical Lithography

M. Suhail Zubairy

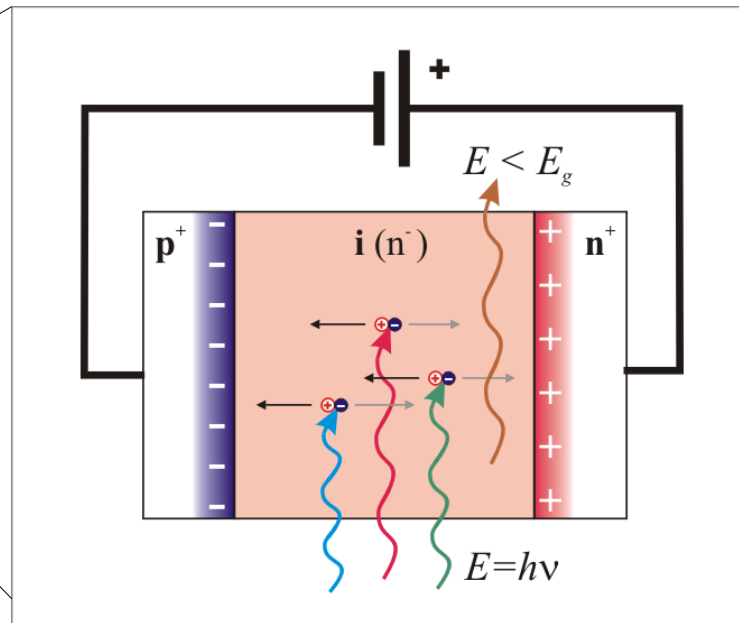
Historical progression of IC feature size and photolithography technologies from Newport web site

Image sensor pixel size

Diffraction-limited pixels with lots of light



S Samsung Semiconductor
ISOCELL HP3 | Mobile Image Sensor ...

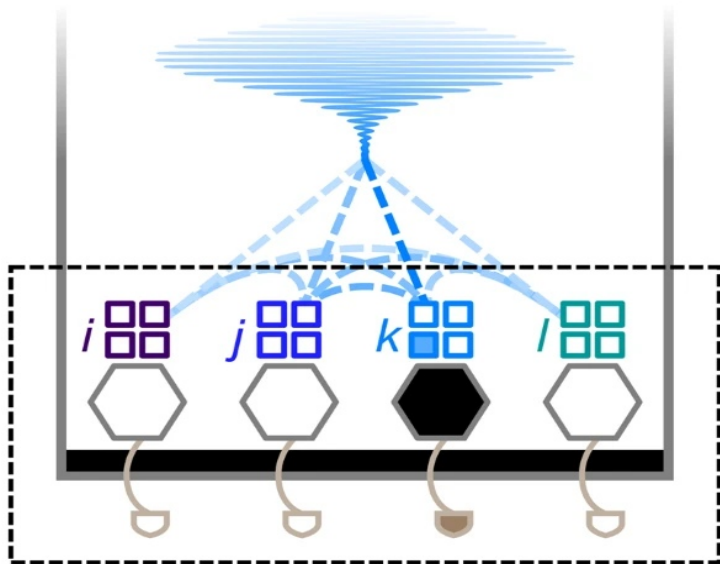


Within one diffraction limited pixel each photon is absorbed by a single lattice site \ll diffraction limit

- Nanoscale feature size manufacturing allows customization of what goes inside the diffraction-limited pixel
- Rather than bulk silicon, which has the properties that it has, make a collection of coupled individual elements, all within 1 wavelength of the light being detected

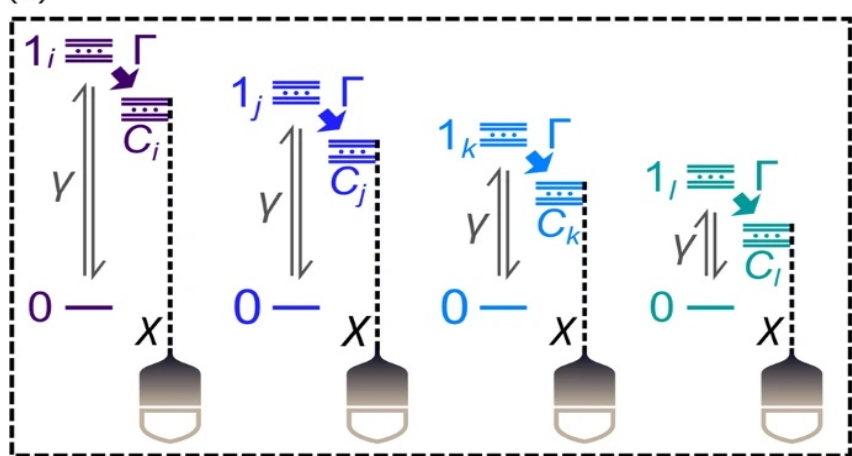
- In a traditional photodetector, like a silicon diode, one material does everything:
 - Absorbs the photon
 - Turns the absorbed energy into excitations (eg e-h pairs)
 - Propagates and maybe amplifies the excitations
- You can't separately control each of these functions
- The point of a nanoscale hybrid is to separately control and optimize each function
 - This opens up more performance parameter space

(a)

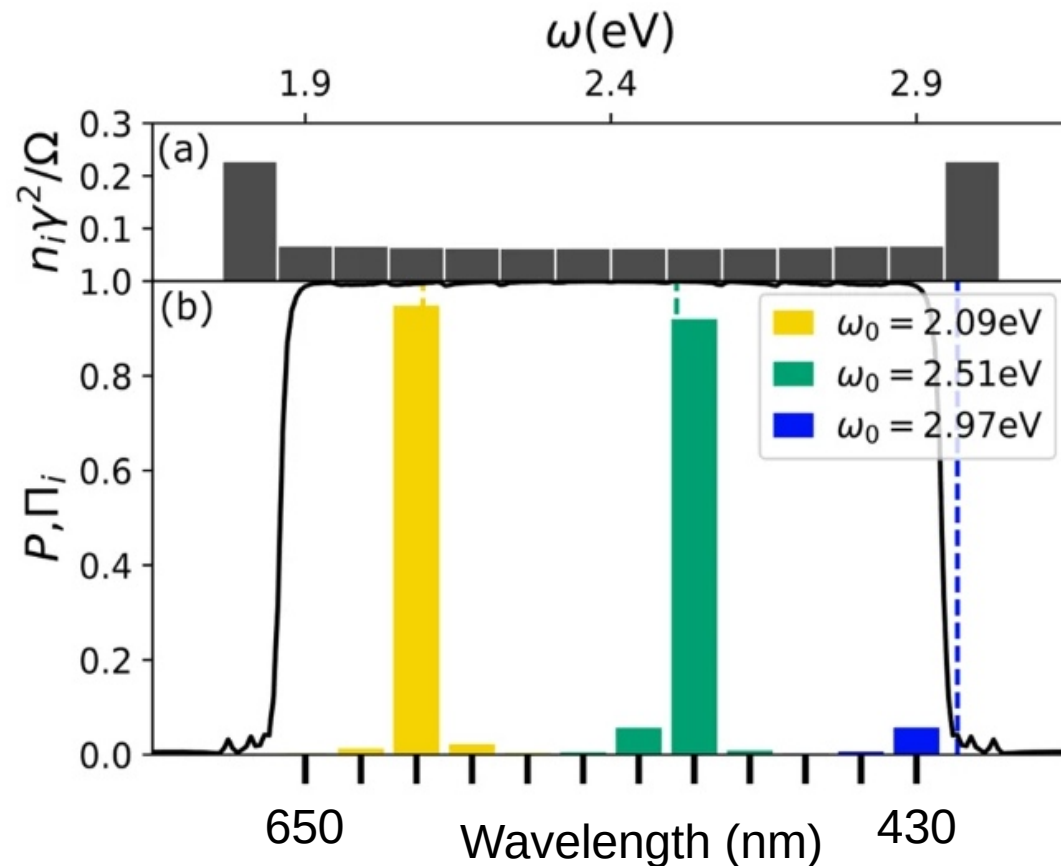


Absorption
(wavelength selective)

(b)

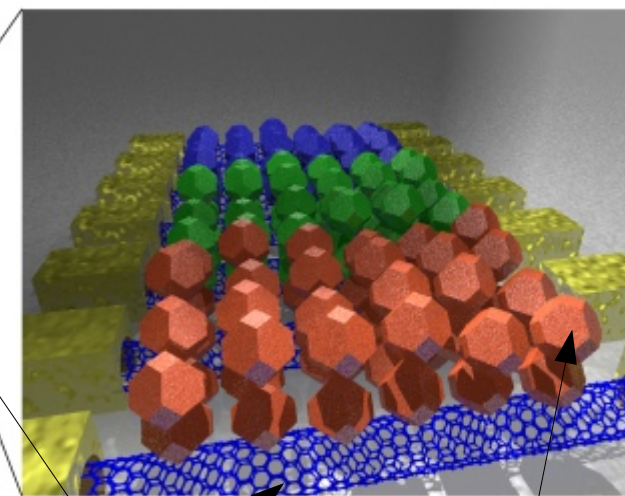
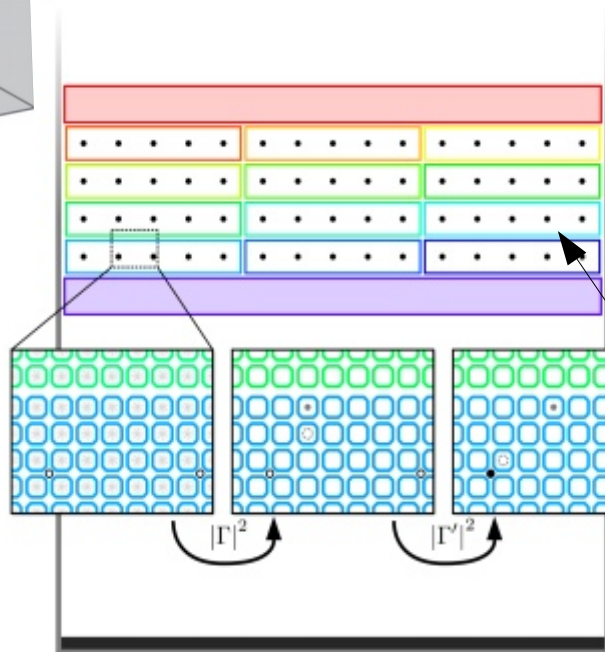
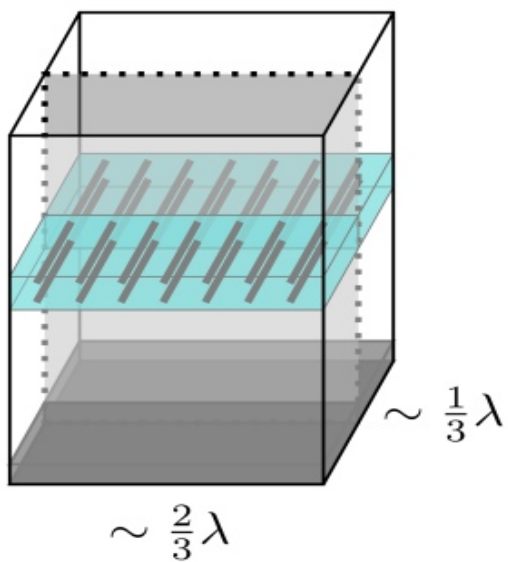
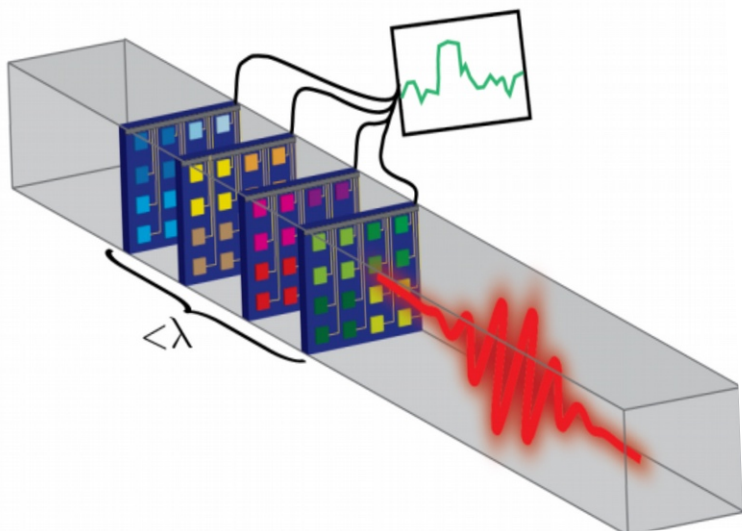


Transduction
(energy from photon turned into electrical signal)



Does not need to be super cold

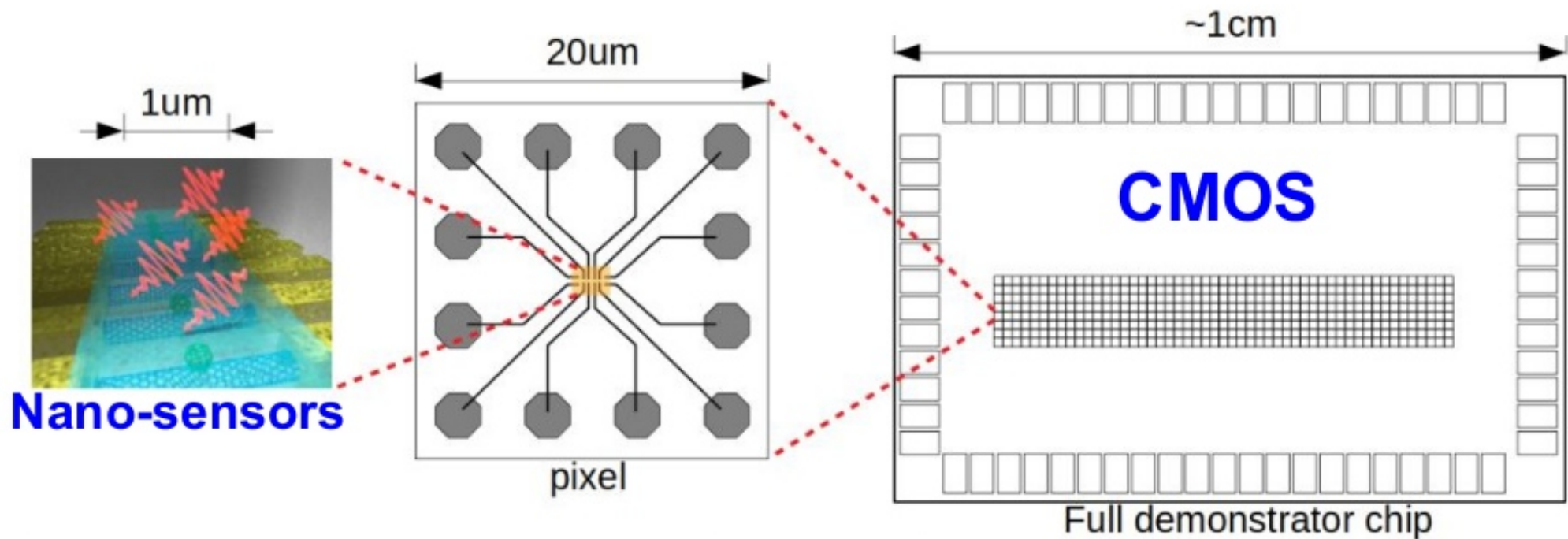
Physical device concept (aka some serious nanoscale patterning)



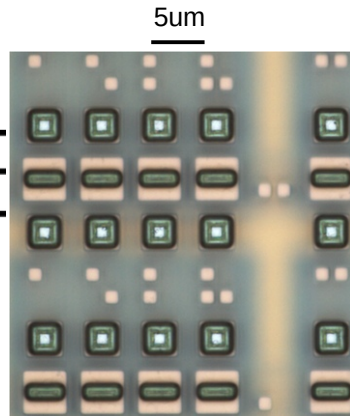
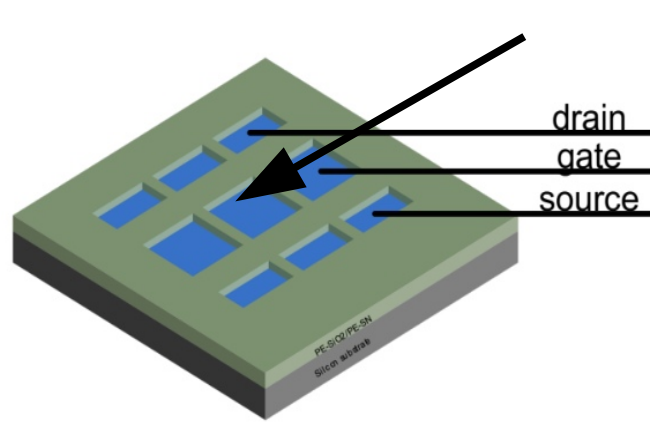
Carbon nanotubes

Coated in quantum dots

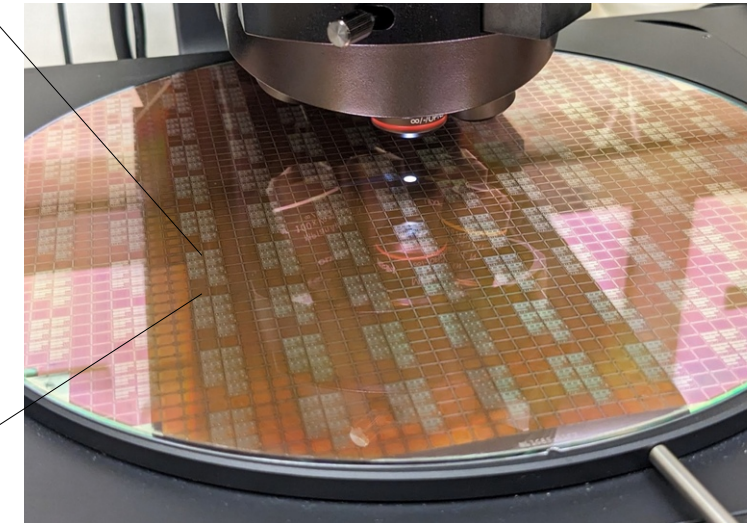
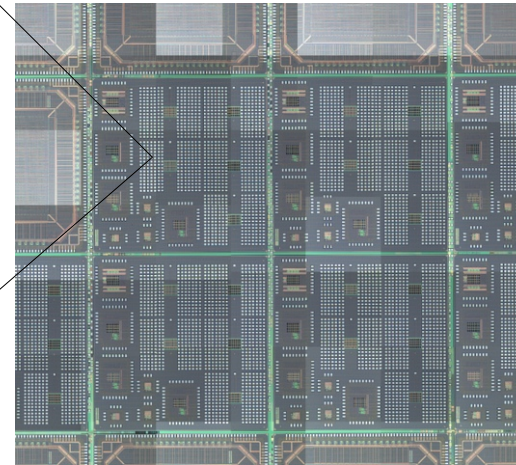
Demonstrator project



CMOS integration work- standard wafers

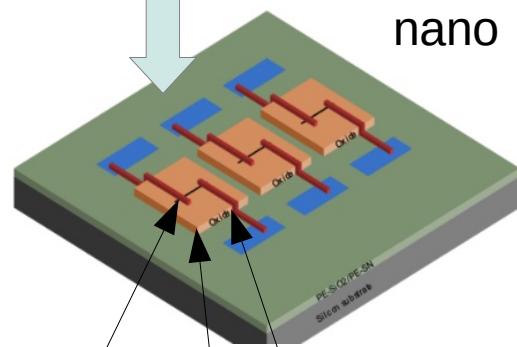


Post-process CMP on finished wafers
~10nm planarity



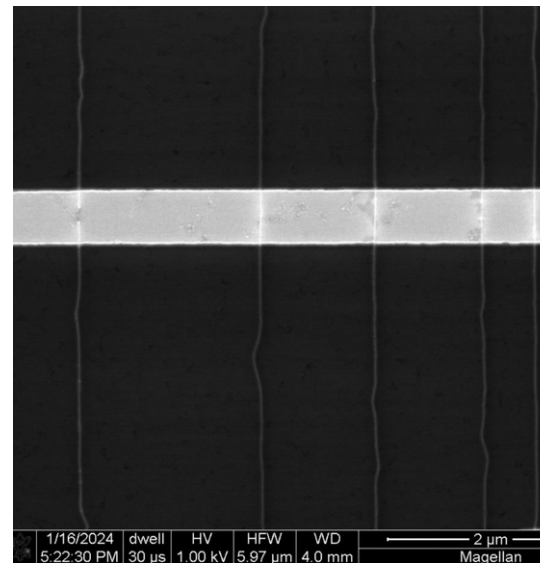
130nm wafer run shared w/LArPix

CMOS
nano

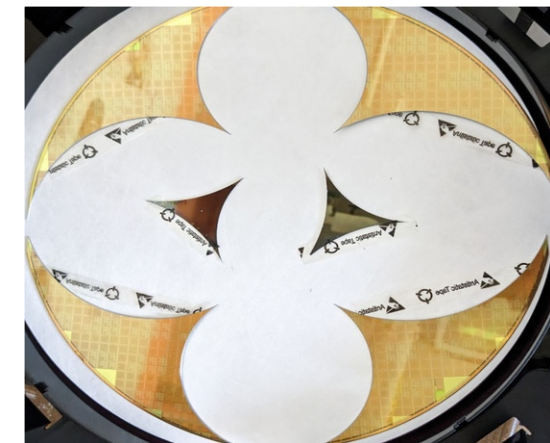


added CNT
added contact
added dielectric

Long parallel
CNTs
Bridging a
trench like
this one

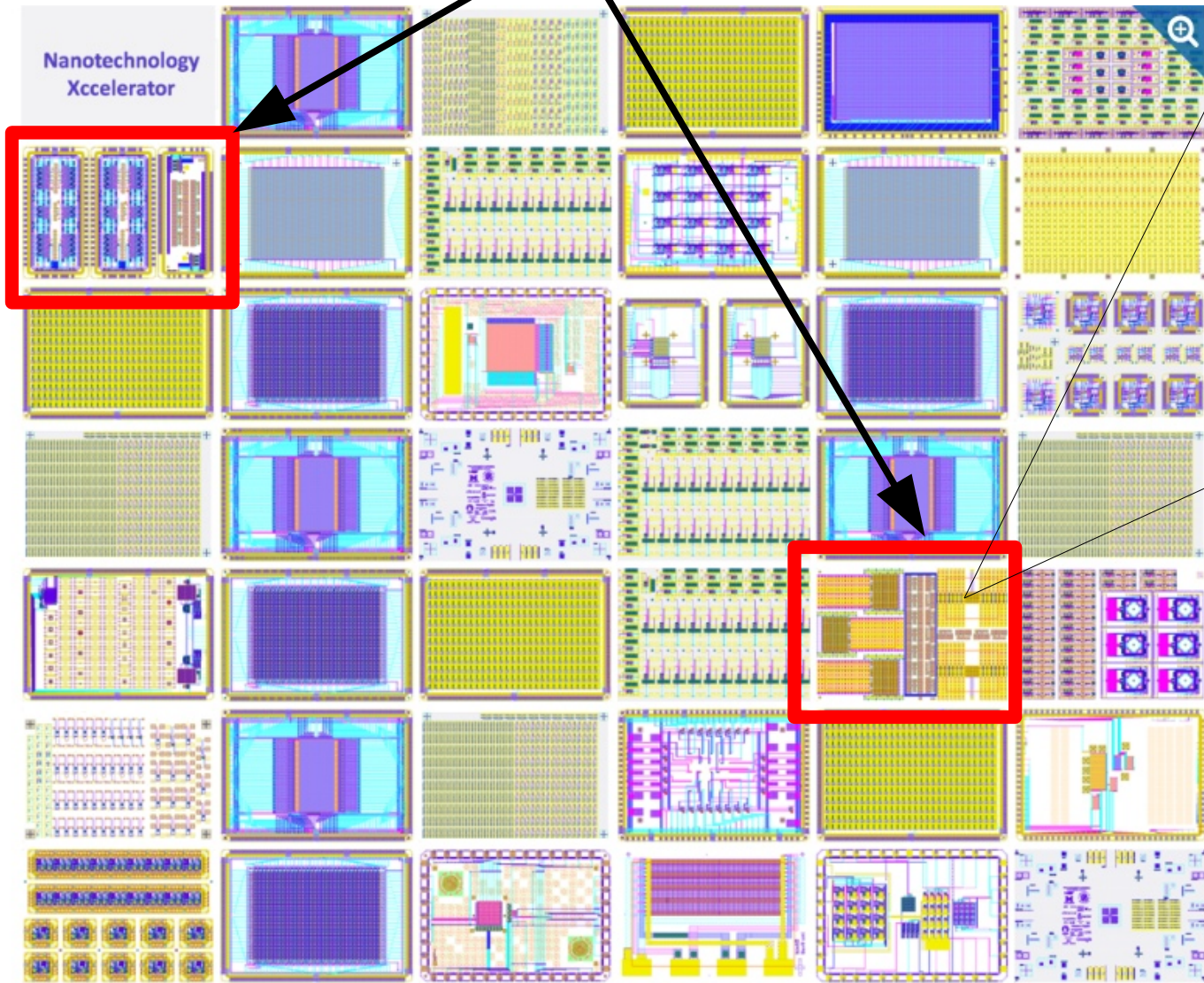


Courtesy of Aligned Carbon, Inc.

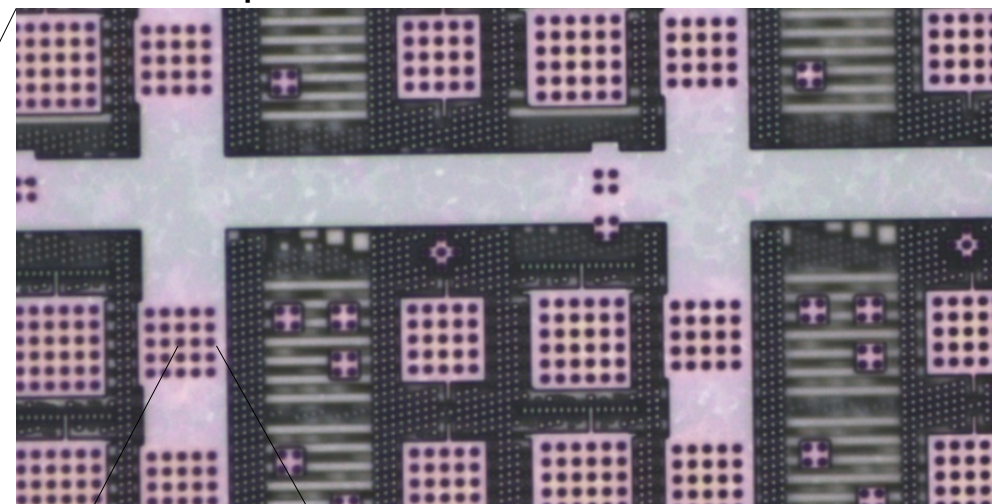


Wafer cored and polished

Our chips

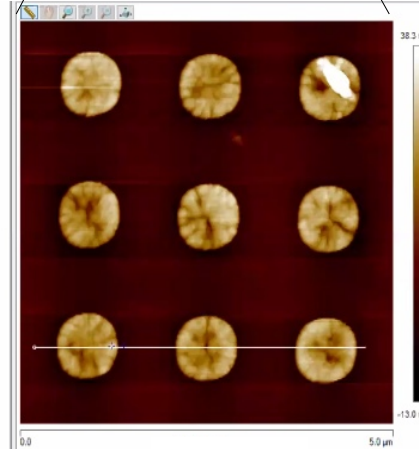


optical

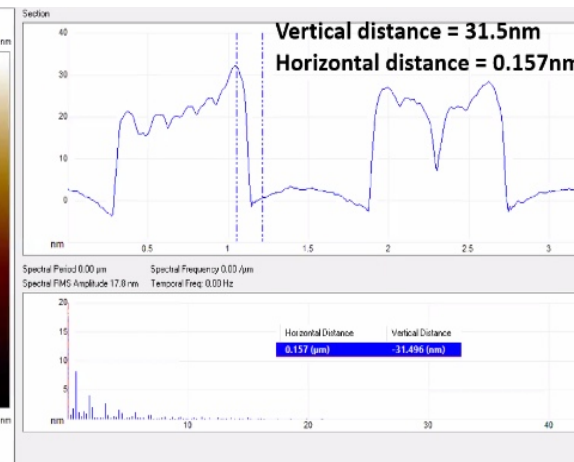


80um

AFM



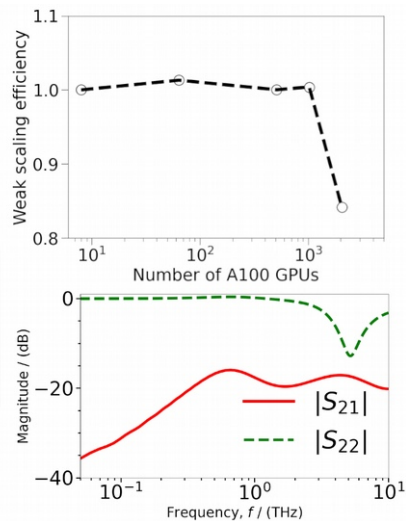
5um



Credit: NIST

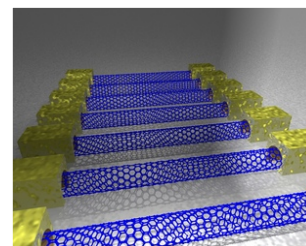
<https://www.nist.gov/programs-projects/nanotechnology-xcelerator>

ARTEMIS

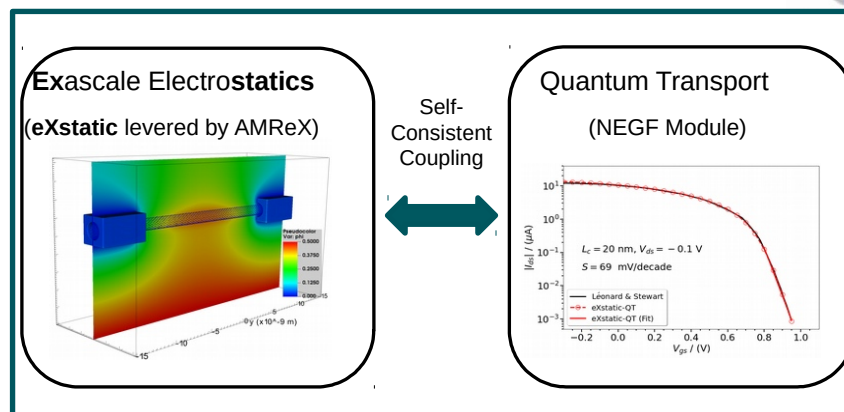
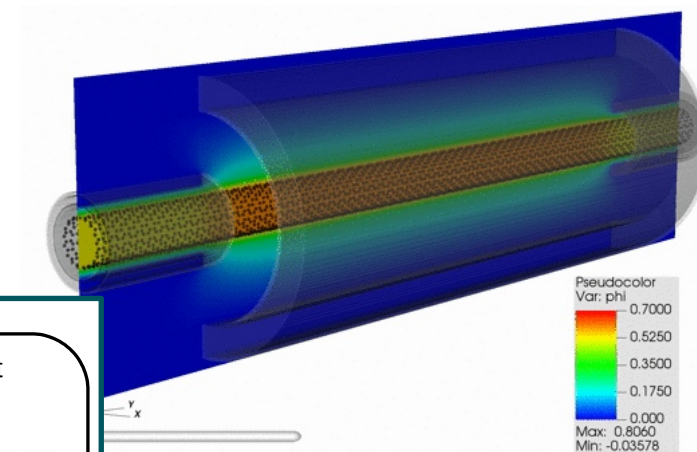


Electrodynamic solution for transmission line **connecting carbon nanotubes to IC inputs**

ELEQTRONeX: Open-source electrostatic-quantum transport framework for modeling transport through nanomaterials on exascale systems

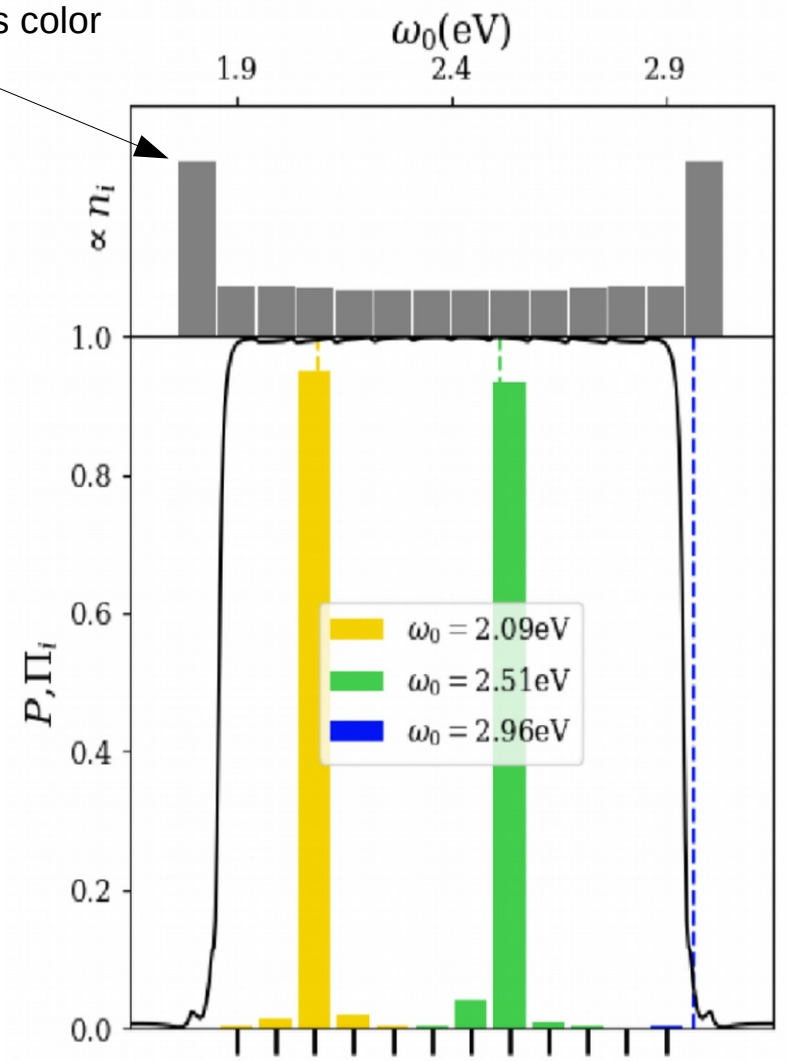
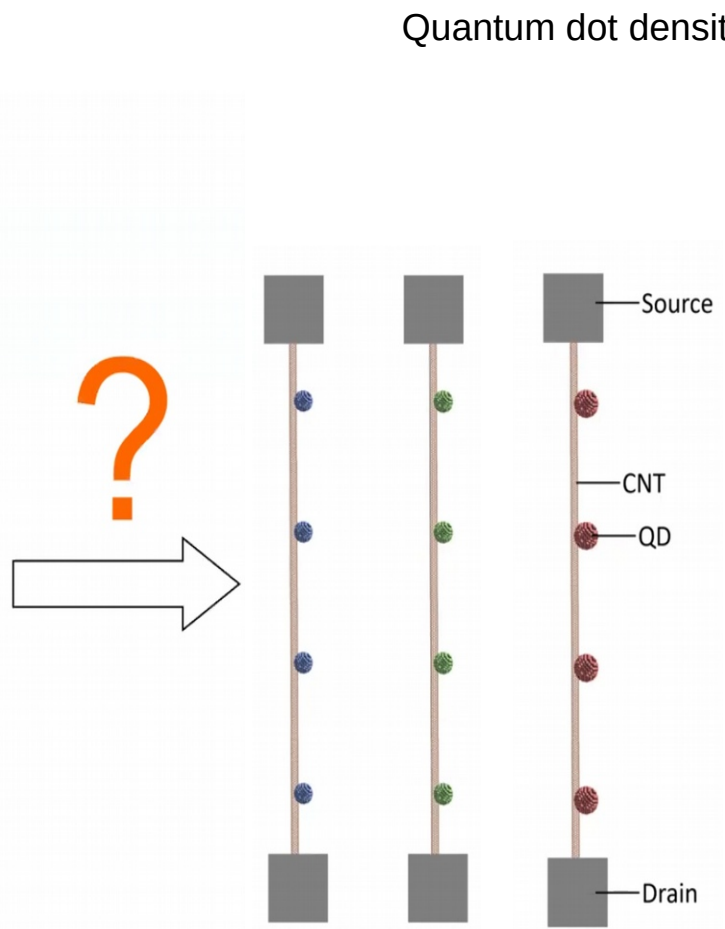
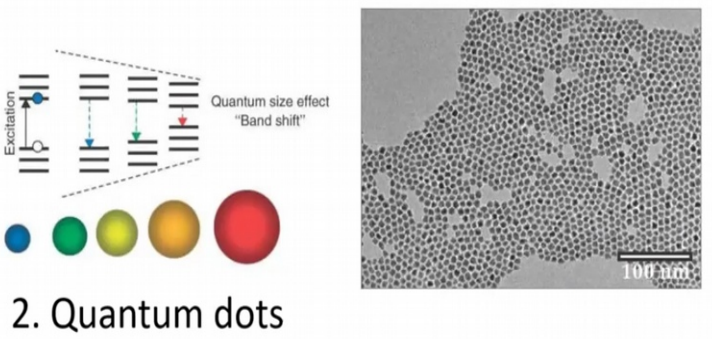
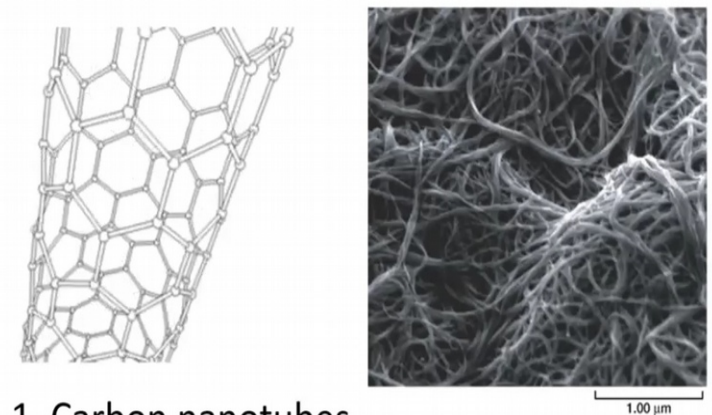


Scalable Modeling

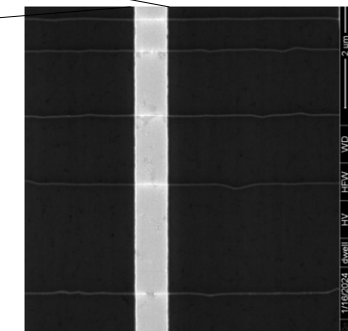
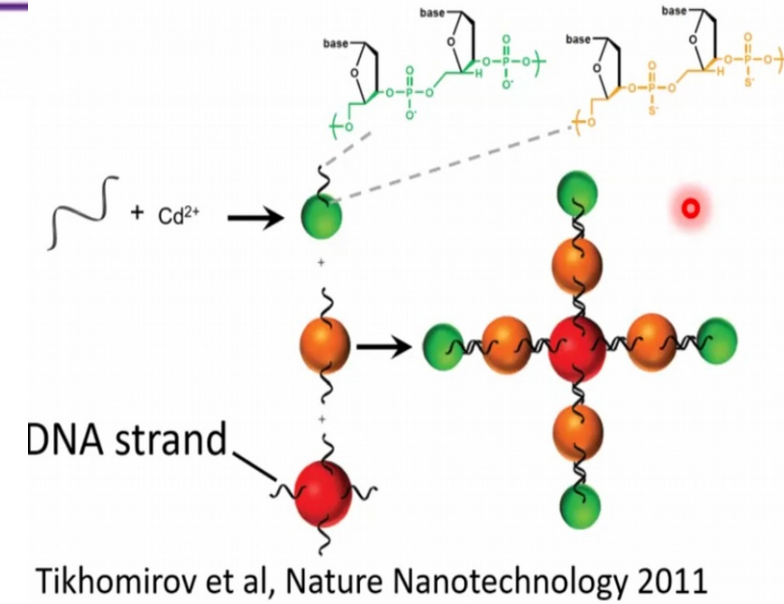
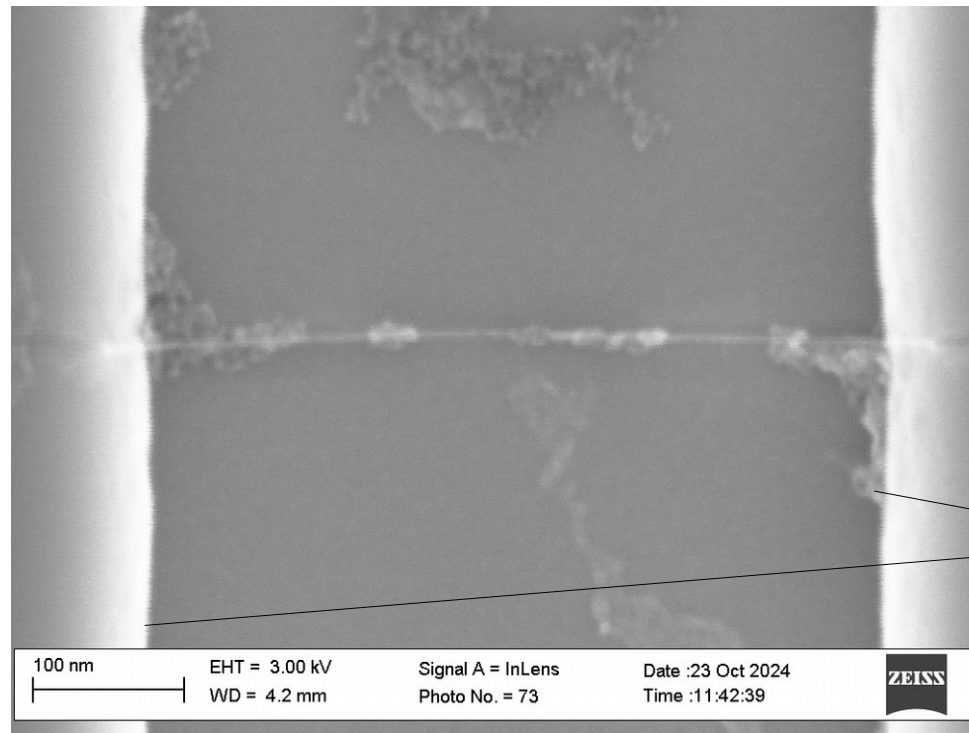
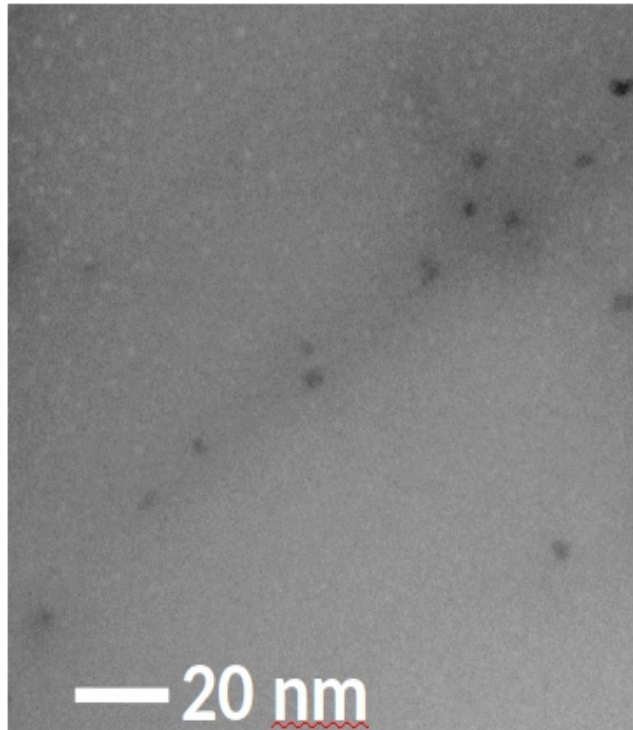
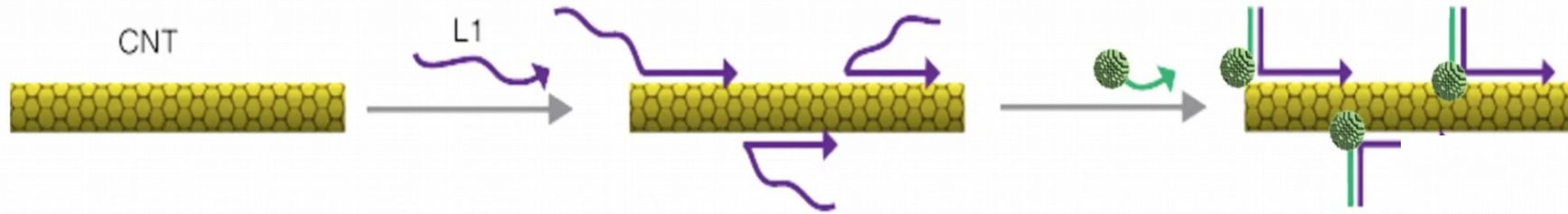


Sawant et al., Characterization of transmission lines in microelectronic circuits using the ARTEMIS solver, JMMCT 2023
 Sawant et al., A Coupled Electrostatic-Quantum Transport Framework for Exascale Systems, IWCN 2023

Adding quantum dots to CNTs



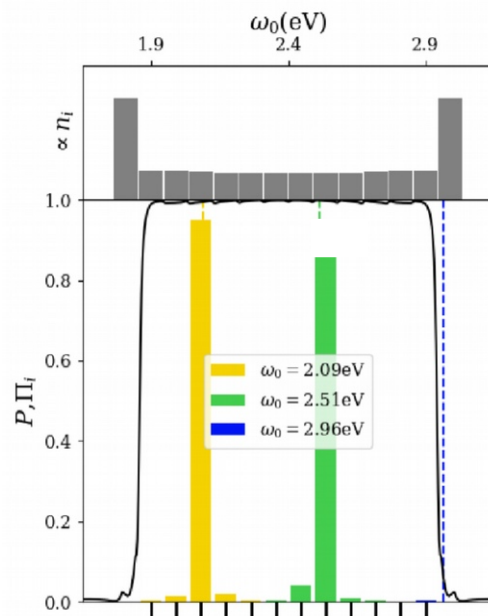
Added QDs using DNA self-assembly



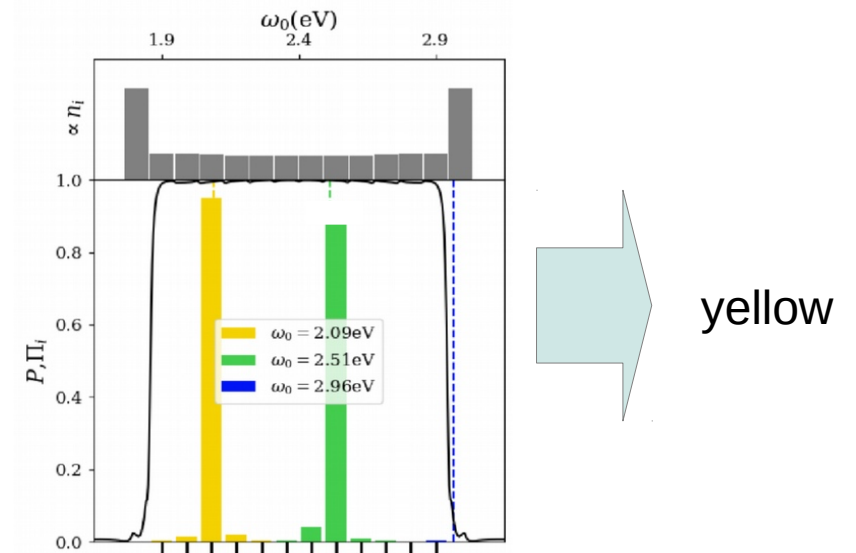
TEM and AFM of quantum dots attached to CNTs

- The retina is not just a sensor, it directly processes the sensory input.
- This saves power down the road
- A nanoscale hybrid sensor could do the same thing
 - Example: spectral peak finding

Could measure counts in each channel,
Then process that info to find the peak



Or



Nanoscale hybrid could directly output the Channel number with the peak counts, Instead of counts in every channel (eg every channel slightly inhibits all others to implement a winner takes all)

- Lithography has been exceeding the diffraction limit for years
 - feature size is given by light-matter interaction, not by light alone.
- Nanoscale photon sensing applies this fact to optical sensors
 - Diffraction-limited pixel sensor made of uniform bulk material is replaced with architecture of nanoscale elements
- Superior performance and new functionality can be achieved
- Not only borrowing for sensing the physical principles from sub-diffraction-limit lithography, but the nanoscale patterning achieved with to those principles is what makes nanoscale sensors possible!
- Wafers have been fabricated in two technologies (130nm standard CMOS) and mid-process wafers (also 130nm) through the NIST Nanotechnology Xcelerator
- Surface planarization, carbon nanotube placement, and decoration with quantum dots have all been achieved.
- Work starting to investigate processing as part of the sensing process itself (before any readout and computing)

BACKUP