Nano-CMOS Photon Imager

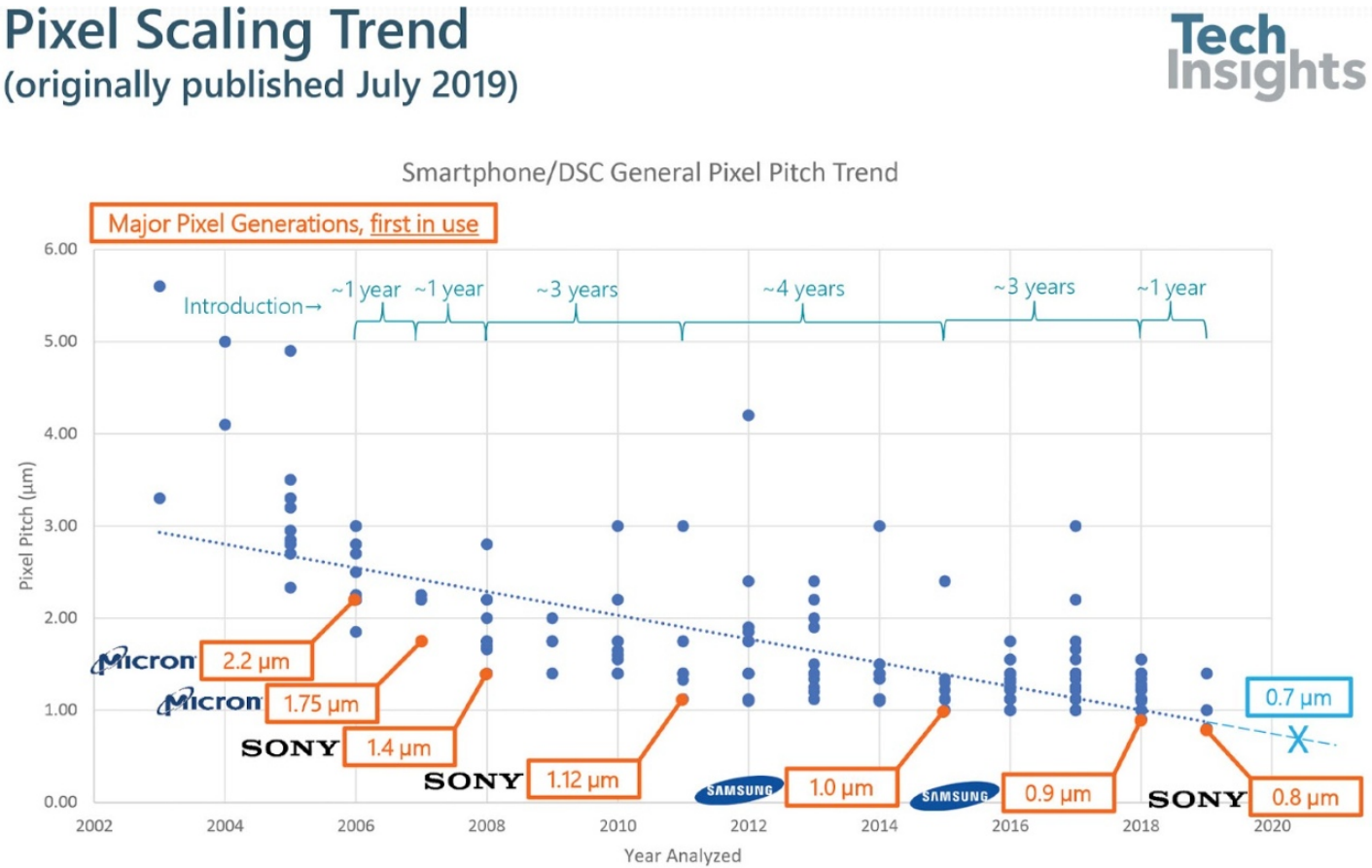
CPAD Workshop,
Stony Brook University
Nov. 30, 2022

M. Garcia-Sciveres, LBNL

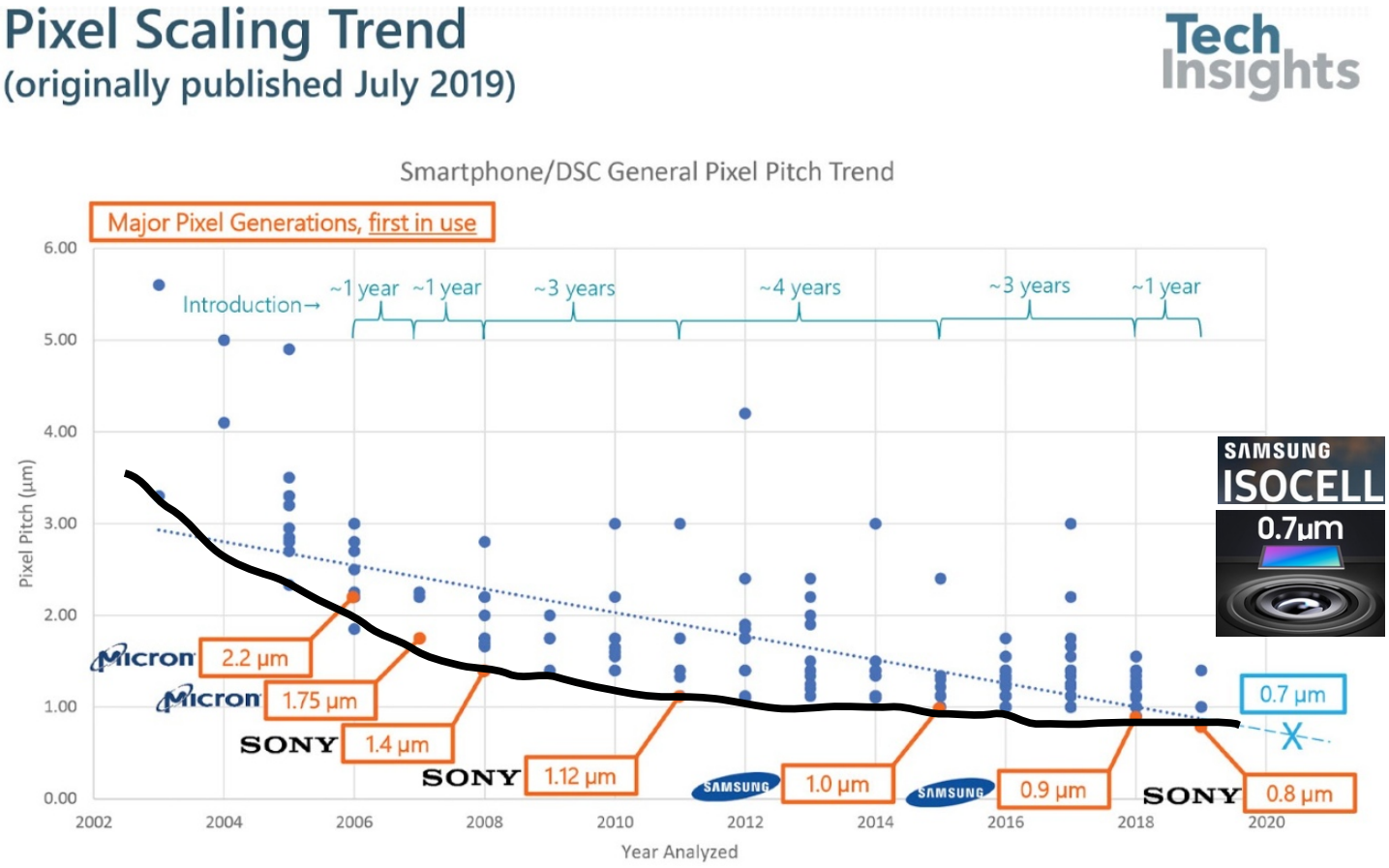
Outline

- Pixels and antennas
- Concept and Microelectronics proposal
  - Work is supported by a Microelectronics Co-Design Research Award
- Development Status
- Conclusion

Are smaller pixels better for imaging?



Are smaller pixels better for imaging?



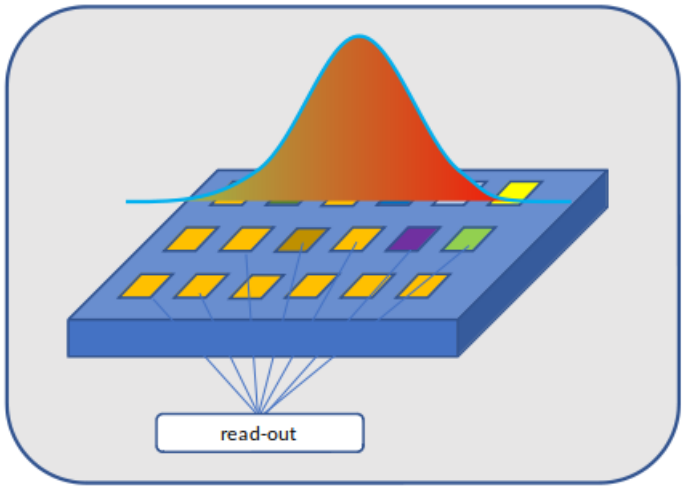
Owl rod pitch

Antennas for Light

- We use pixels much smaller than the wavelength of electromagnetic radiation all the time- they’re called antennas
- One can do different things with antennas and waves than with full absorption optical pixels
- It gets even more interesting when considering the interaction of the quantized EM field with an antenna
- Turns out this touches many subjects of interest outside of HEP

CPAD 2019 Workshop Origin

subwavelength elements collectively interacting with the photon field



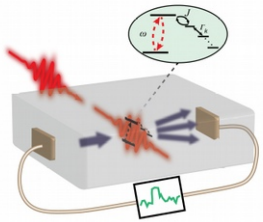
CPAD Instrumentation Frontier Workshop 2019

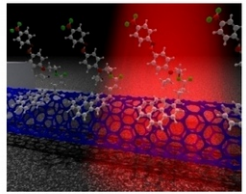
University of Wisconsin-Madison

Novel Designs for Few Photon Detection Based on Quantum and Nanoscale Systems

Mohan Sarovar, Catalin Spataru, Steve Young, Annabelle Benin, Kevin Bergemann, Patrick Doty, Andrew Vance, and François Léonard

Sandia National Laboratories, Livermore, CA





Sandia National Laboratories

DARPA

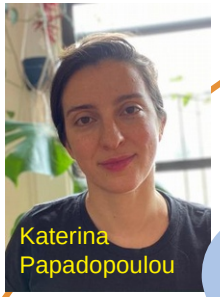
Topic was a good match to National Microelectronics Initiative FOA

MICROELECTRONICS CO-DESIGN RESEARCH

DOE NATIONAL LABORATORY PROGRAM ANNOUNCEMENT NUMBER:
LAB 21-2491

ANNOUNCEMENT TYPE: INITIAL

Multidiscplinary team with broader focus than HEP

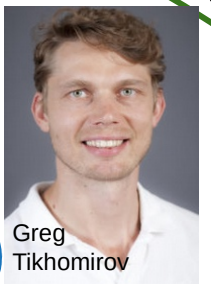

Katerina Papadopoulou

IC design / microfab


Weilun CHao

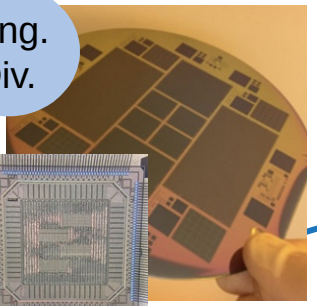
Ctr. For X-ray optics


Mi-Young Im


Greg Tikhomirov

nanotech

Eng. Div.



UC Berkeley EECS


Yuan Mei

Nuc. Sci. Div.

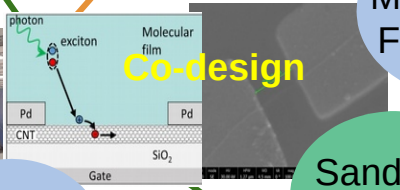

Archana Raja


Tevye Kuykendall

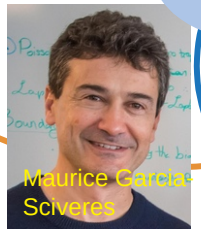

Ricardo Ruiz

Molecular Foundry

Physics Div.



Sandia NL Nanotech.


Maurice Garcia-Sciveres

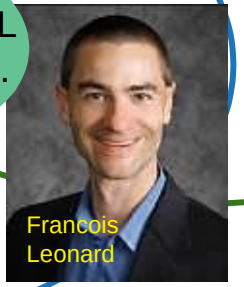
(PI)

Comp. Research Div.


Jackie Yao


Andy Nonaka

Sim.l theory

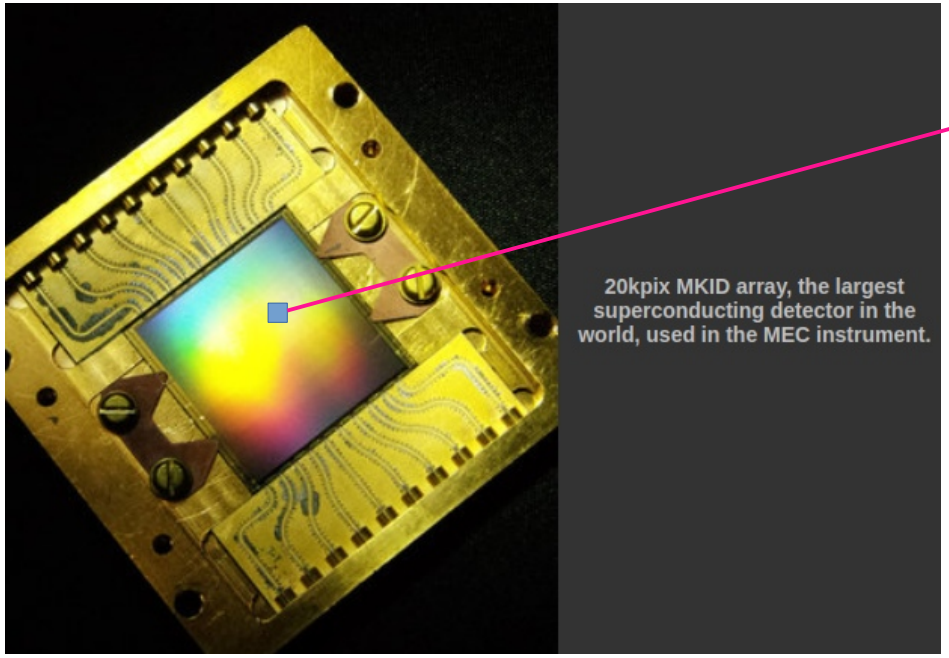

Francois Leonard

Focus of Nano-CMOS project

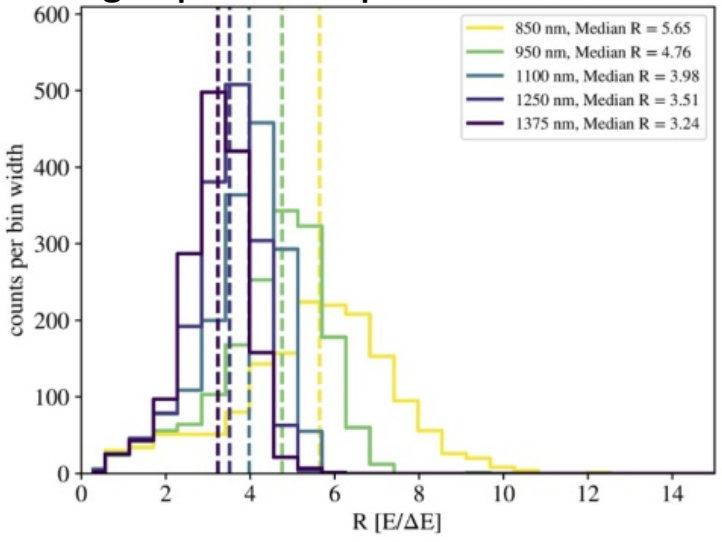
- Produce a demonstrator device that looks like a CMOS sensor
  - Built up starting with a CMOS IC
- But functions differently, with nano-antennas interacting with the quantized EM field
- It detects (counts) single photons, and records the wavelength of each one: A spectrally-resolved single photon imager
  - Such things exist already, but are not true single photon measurement devices.
  - Example follows

MEC @ Subaru

https://web.physics.ucsb.edu/~bmazin/



Single photon spectral resolution



ASSUMES EACH PULSE IS A SINGLE PHOTON
(Measures energy deposits, no photons. Runs at 0.1K)

Actual spectral information on single photons

arXiv:2205.05817

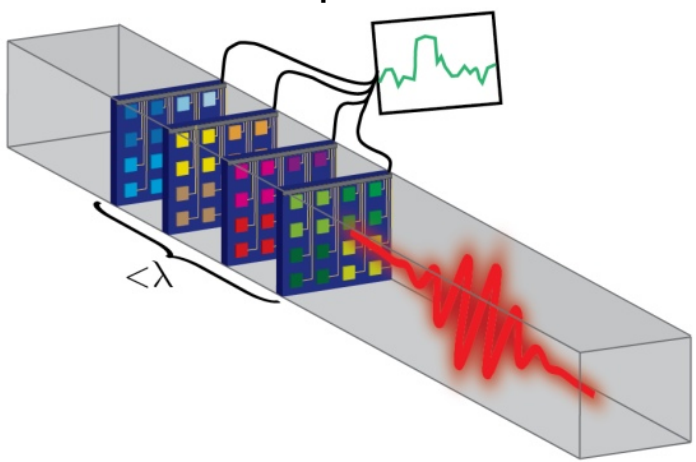
Nanoscale Architecture for Frequency-Resolving Single-Photon Detectors

May 2022

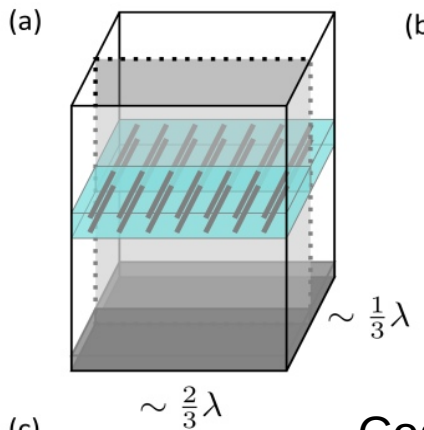
Steve M. Young, Mohan Sarovar, and François Léonard*

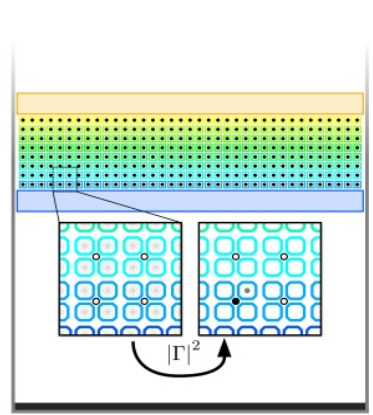
Sandia National Laboratories, Livermore, CA, 94551, USA

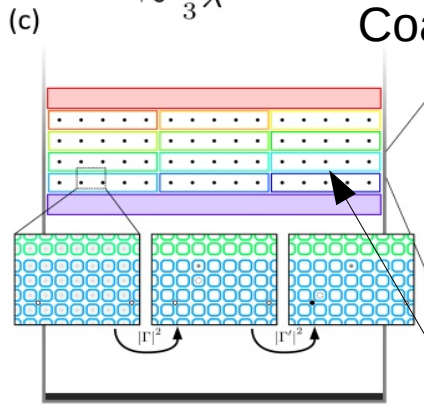
concept



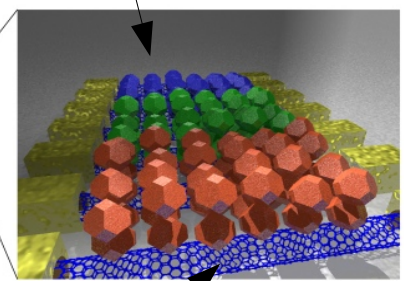
Possible implementation







Coated in nanoparticles



Carbon nanotubes

Does not need to be super cold

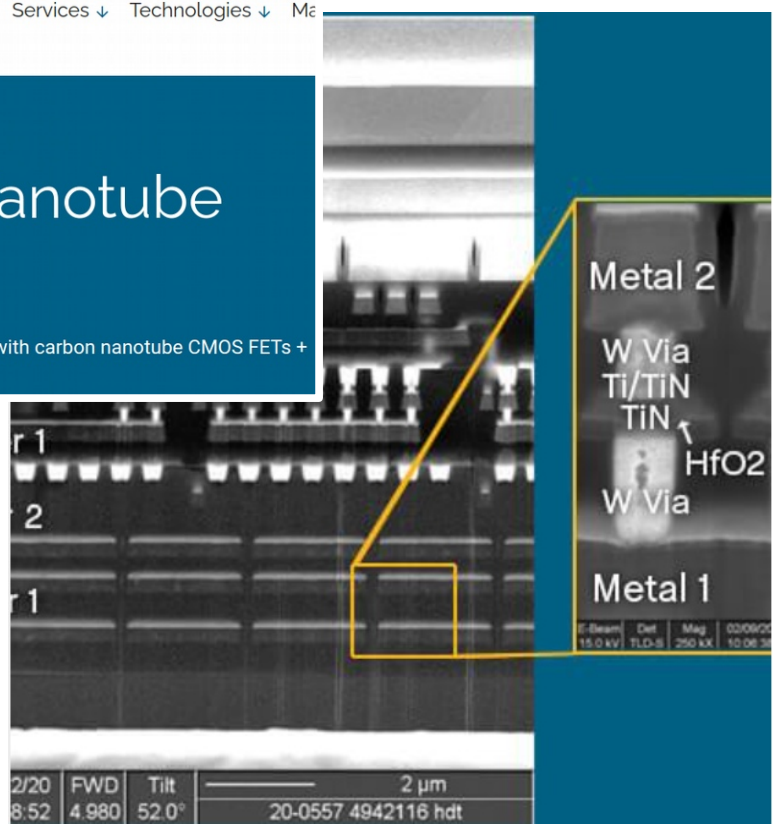
Can this implementation be realized?

CNTFETs fairly mature

skywater Services ↓ Technologies ↓ Ma

Carbon Nanotube SoCs

High-density, stackable SoCs with carbon nanotube CMOS FETs + ReRAM

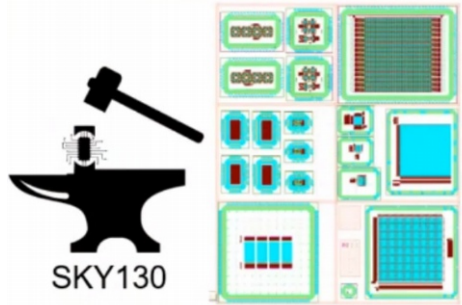


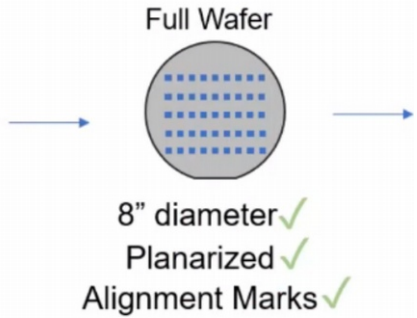
Fine pitch back end platform available soon

Nanotechnology Accelerator Program NIST

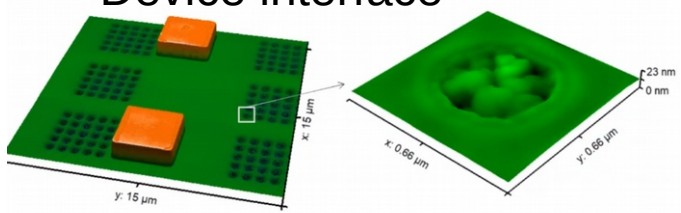
Aggregate Broad Use Maskset
Google Sponsored Reticle

Order Mid-production Wafers
Made for manufacturing research

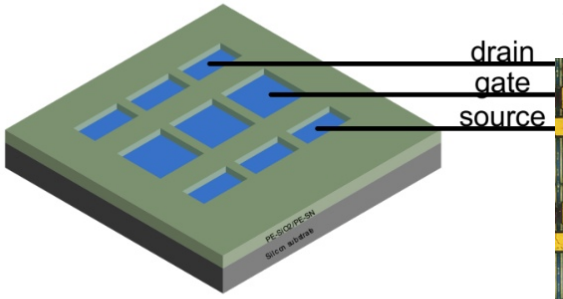




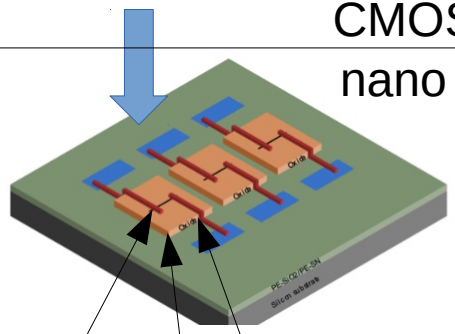
Device interface



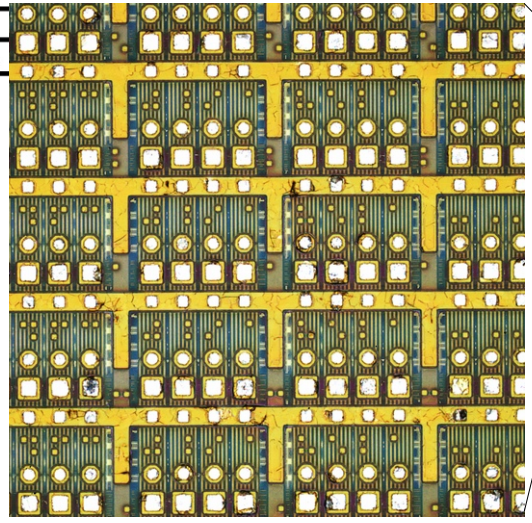
What have we done so far? - CMOS



CMOS
nano

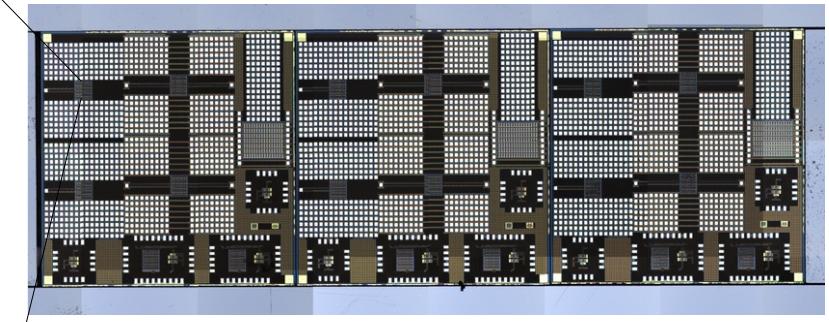


10um



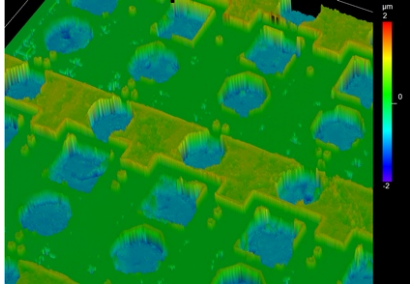
1mm

TSMC 180nm pad array and
CNT readout preamp prototype



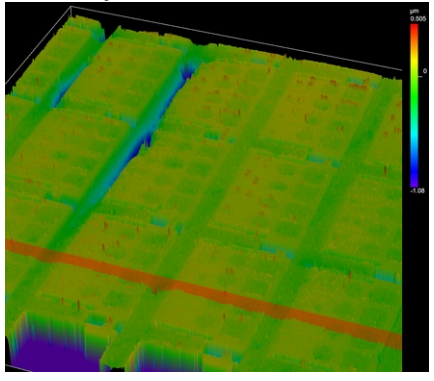
3 chips embedded in silicon

Not planar



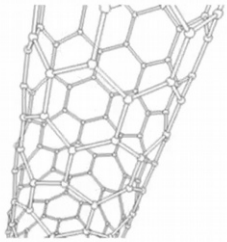
3um
topography

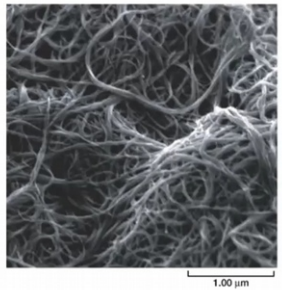
polished



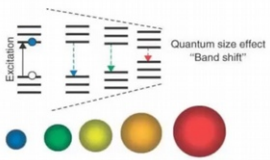
60nm
roughness

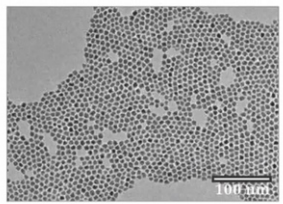
What have we done so far? - CNTs





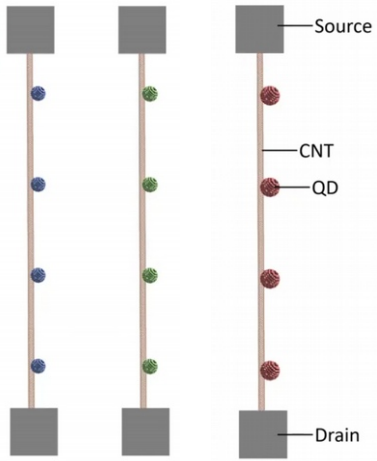
1. Carbon nanotubes



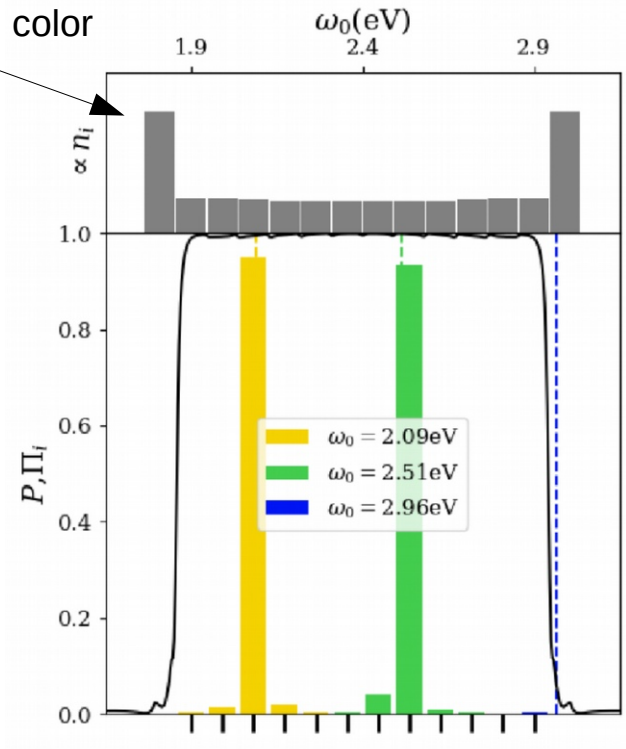


2. Quantum dots

?

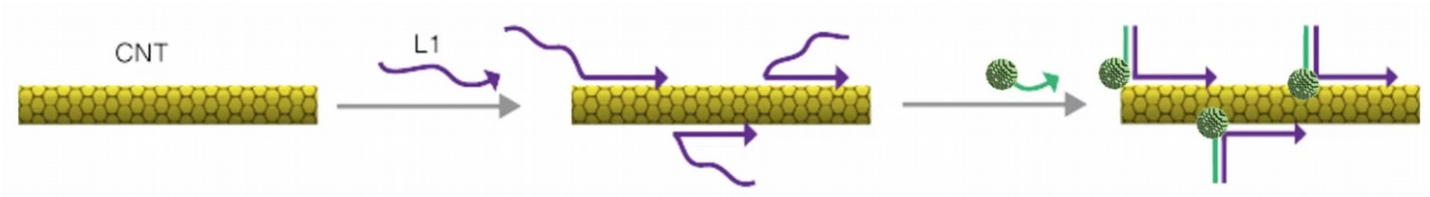


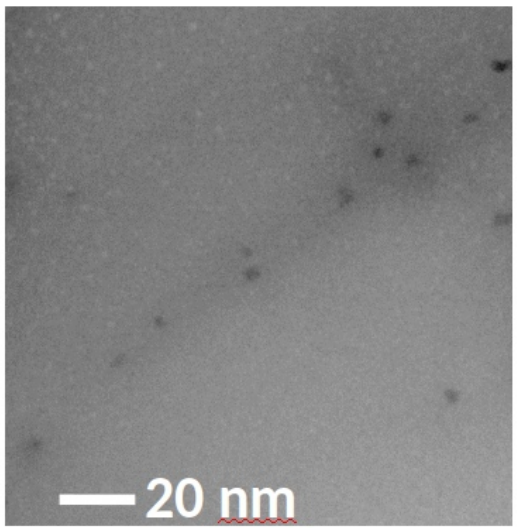
Quantum dot density vs color

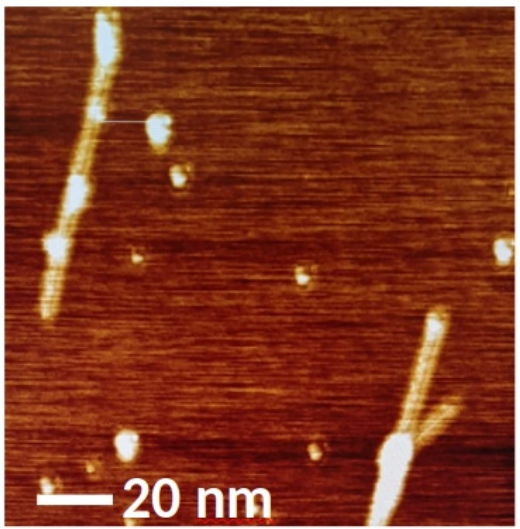


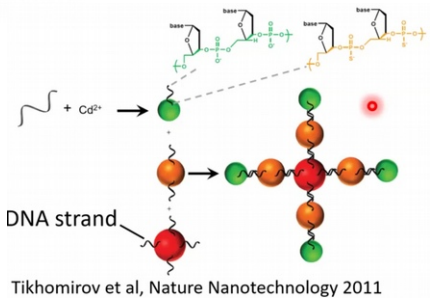
Resulting resolution from above density distribution

Quantum Dots onto CNTs





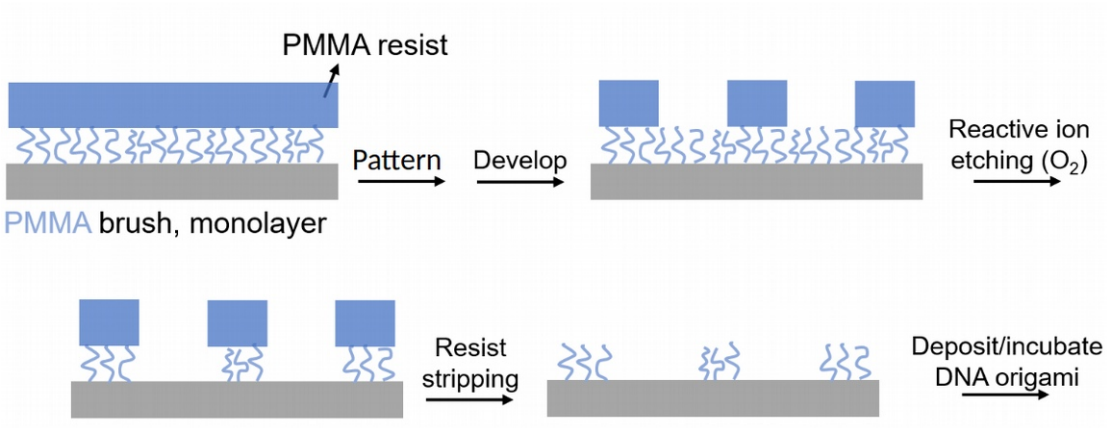


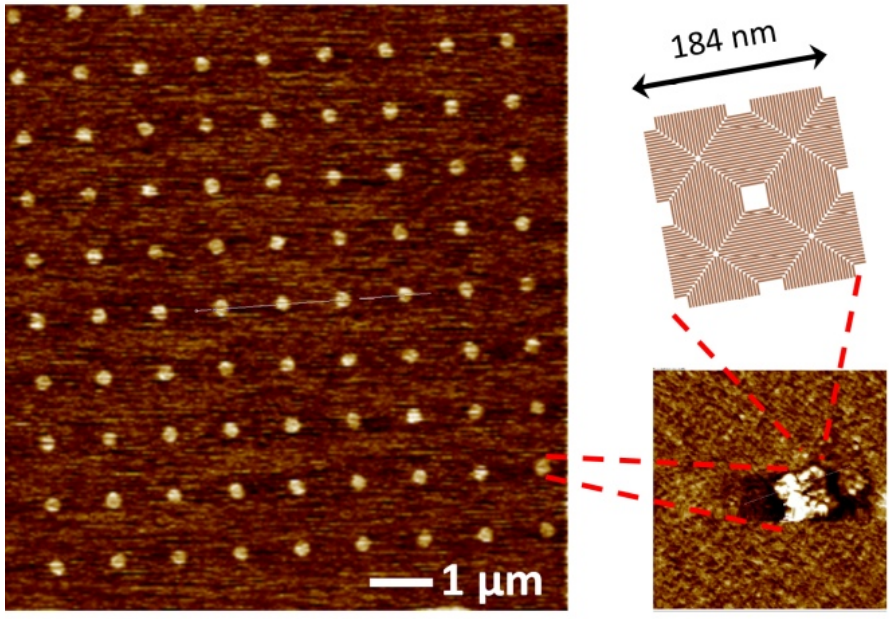


TEM and AFM of quantum dots attached to CNTs

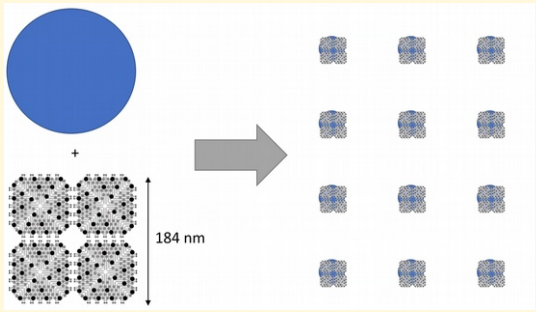
Placing CNTs on predefined locations

Lithographic definition to DNA patches where you want devices to self-attach





DNA origami structures will attach onto patches carrying CNTs with them



What have we done so far? Other

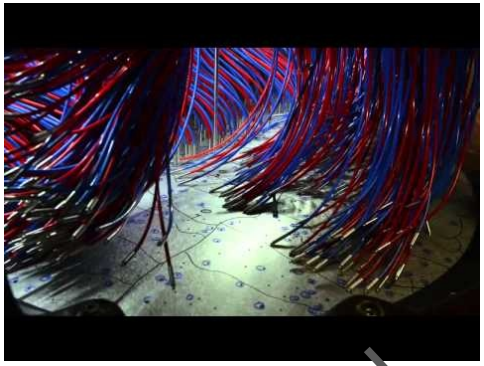
- Developed electrical simulation code for heterogeneous system
  - arXiv:2208.04371
- Tuned CNT dispersion from solution and adhesion
- Produced hexagonal BN gate dielectric samples
- Ported chip design to Skywater 130nm and TSMC 130nm
  - eFabless.com : NanoCMOS public project
- Validated Pd electrode metal film deposition and e-beam lithography on ASIC
- Made progress on lithographic alternative to CNT + quantum dots using TMD 2-D material films (Transition-metal dichalcogenides)

Conclusion

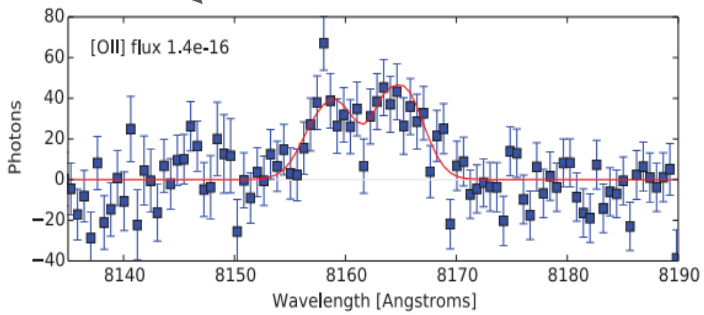
- A quantum superposition of sub-wavelength sensors is being developed as a photon-counting, spectrally-resolving imager
  - Counter to the conventional rule that there is no benefit to making pixels smaller than the resolution of the optics- ultimately limited by the wavelengh
- Microelectronics technology trends make this kind of device viable now
  - New devices such as carbon nanotubes approaching commercial mainstream
  - Growing support for heterogeneous integration of new materials on CMOS
- Development was a good match to a multidisciplinary effort funded by a Microelectronics co-design research award.
  - Funding from HEP, BES and ASCR programs

B A C K U P

Spectral resolution for dark energy surveys



fiber spectrograph



λ/Δλ ~ 2000

Nano-devices on CMOS back ends

CMOS Integration Critical for Measurements

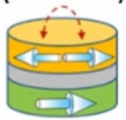
NIST

The Sauce: New devices and materials are continually proposed by the academic community

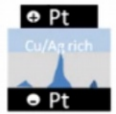
Resistive switching memory (ReRAM)

Phase change memory (PCM)

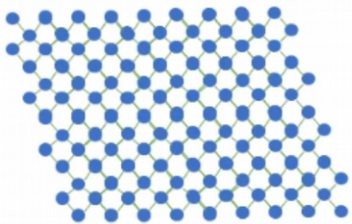
Spin torque transfer (STT - RAM)



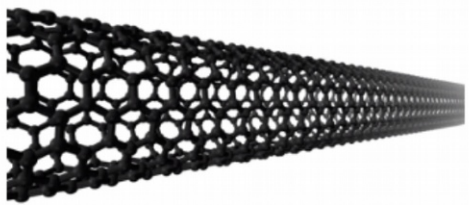
Conductive bridge (CB-RAM)



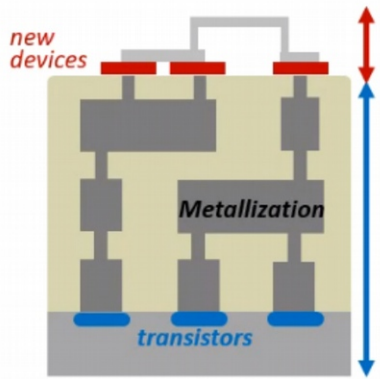
2D Materials



Nanotubes



Reliable monolithic integration is a requirement for experimental prototyping



New devices
ACADEMIC RESEARCHERS

CMOS circuitry
FOUNDRIES