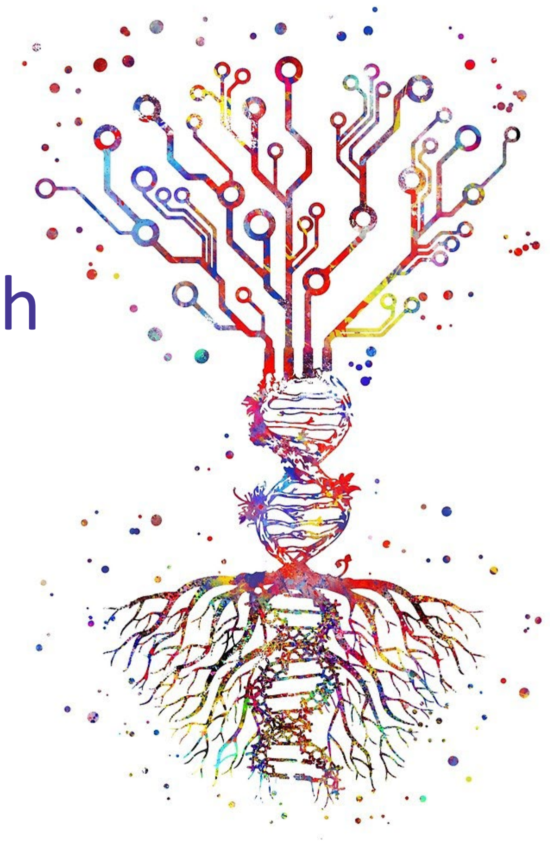
Self-assembly of photon transducers based on carbon nanotubes and quantum dots, and their integration with CMOS electronics guided by DNA

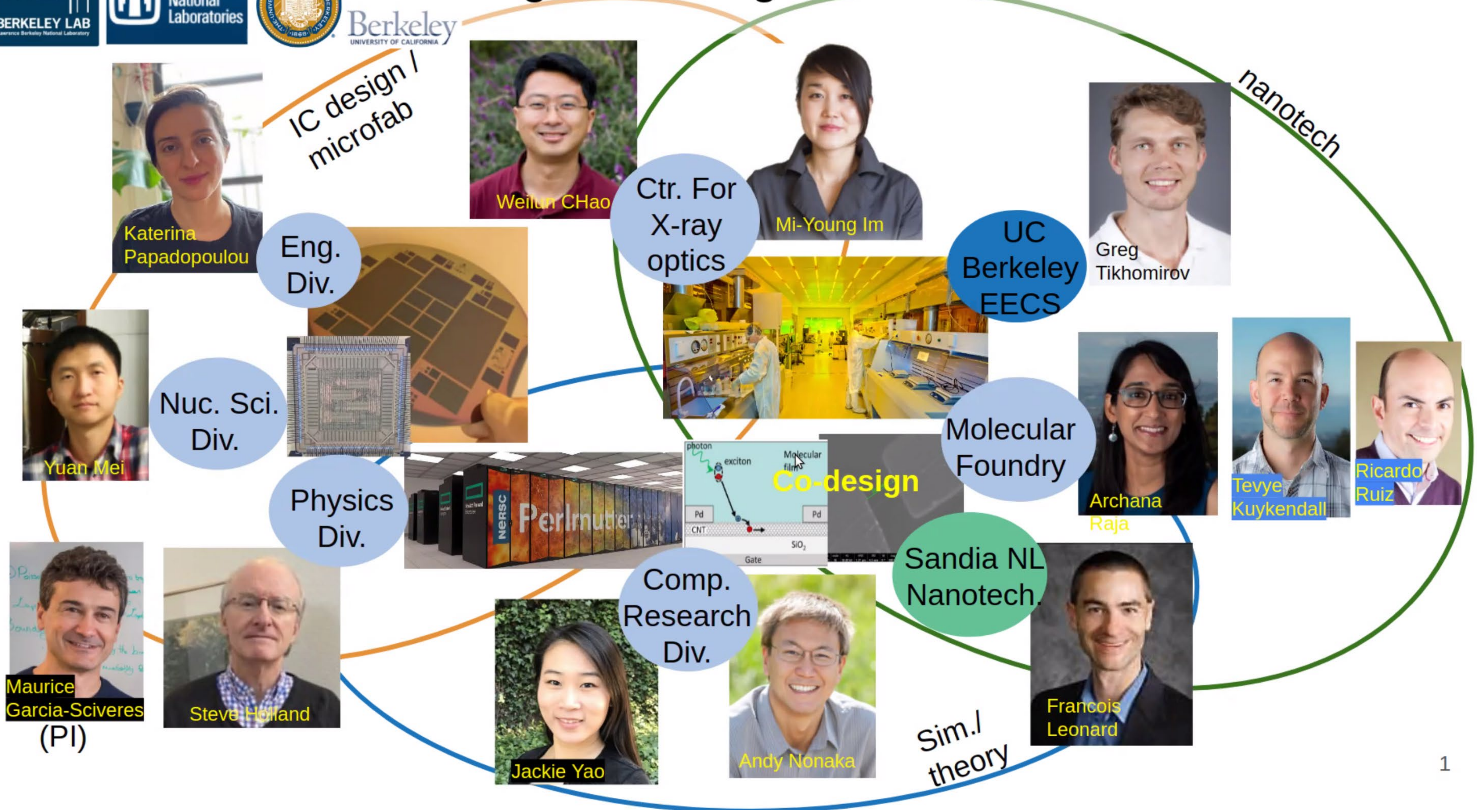


Greg Tikhomirov, Berkeley EECS

tilabberkeley.com

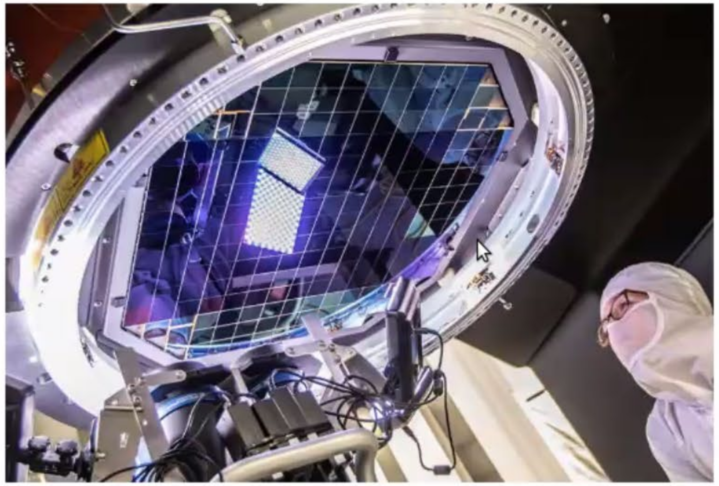
@nanoassembly

Co-Design and Integration of nano-sensors on CMOS

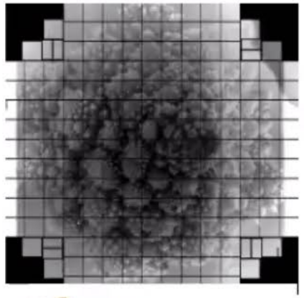


Single photon sensor with color resolution

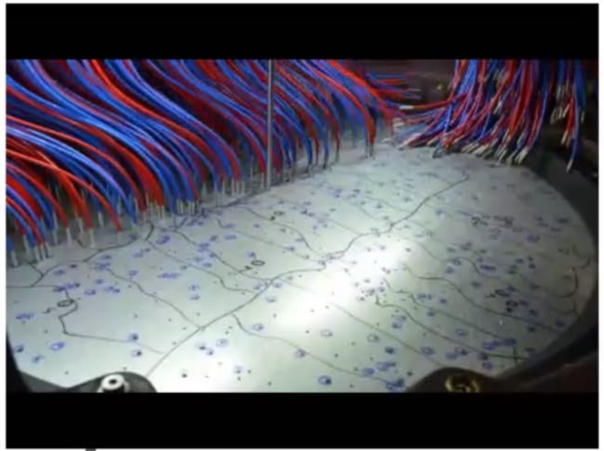
From filter or dispersive based to Bio-inspired



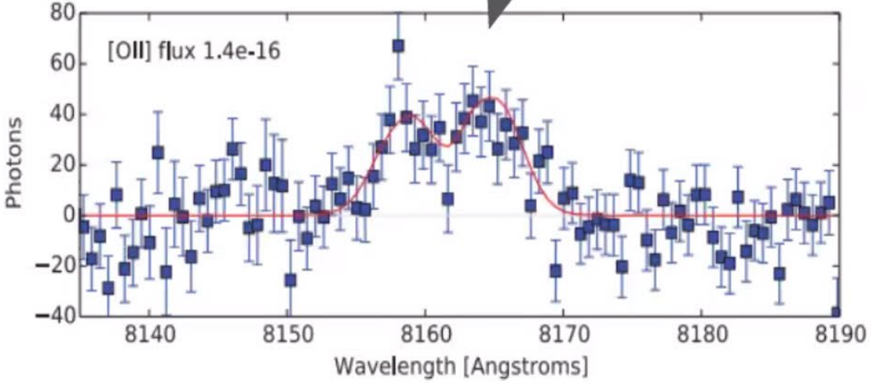
Vera Rubin Observatory CCD focal plane

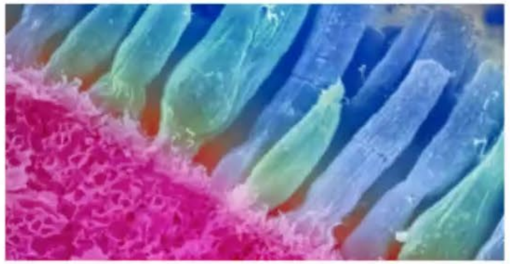


filter wheel



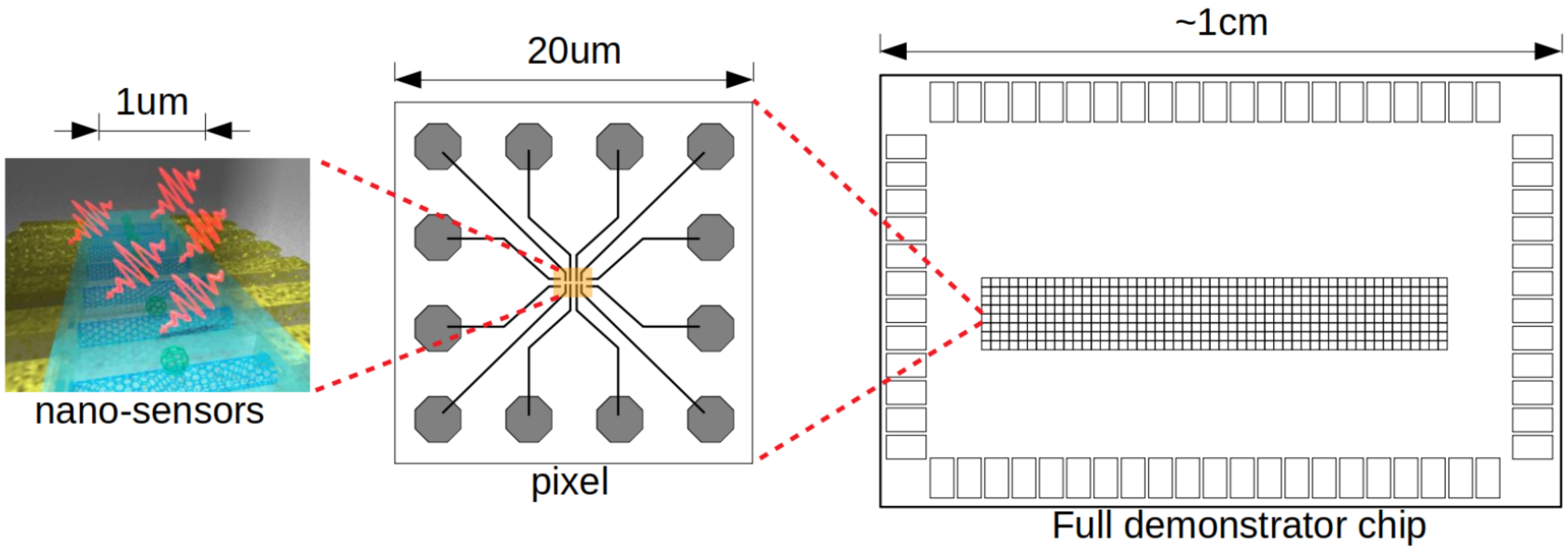
fiber spectrograph



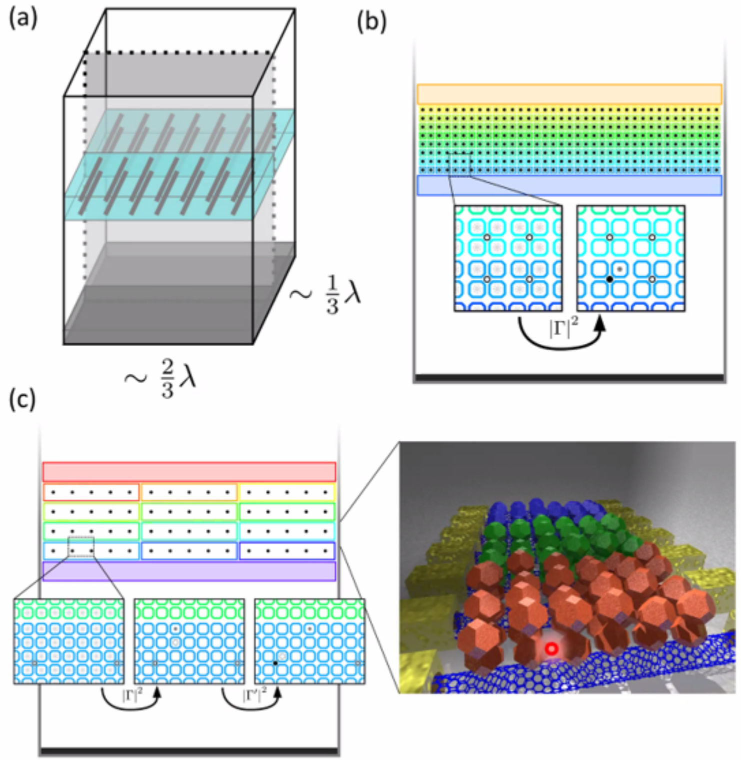


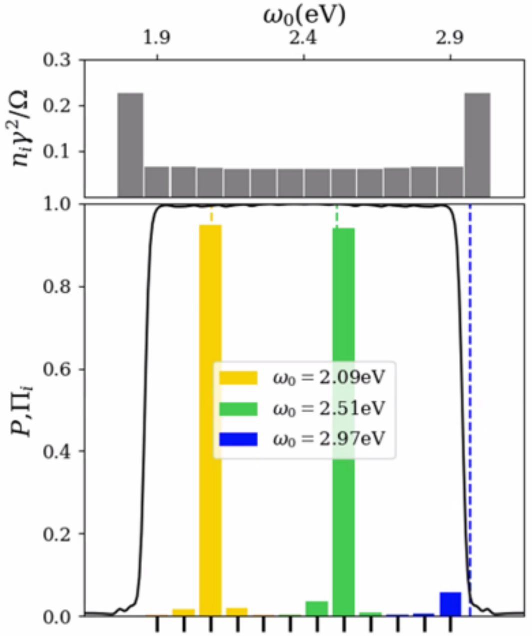
cones

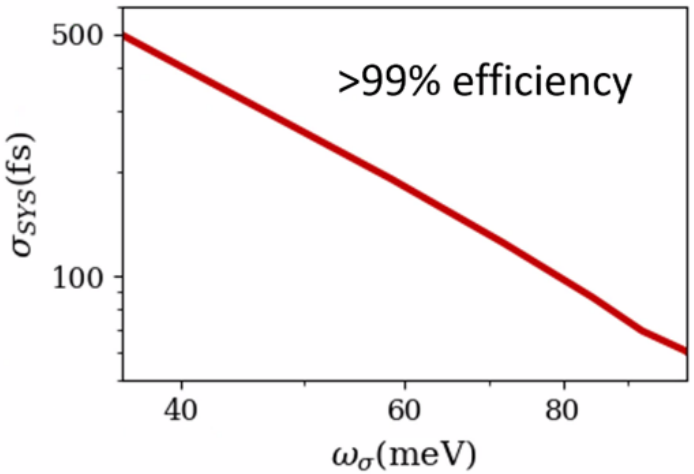
Single photon sensor with color resolution



Frequency-Resolving Single Photon Detection







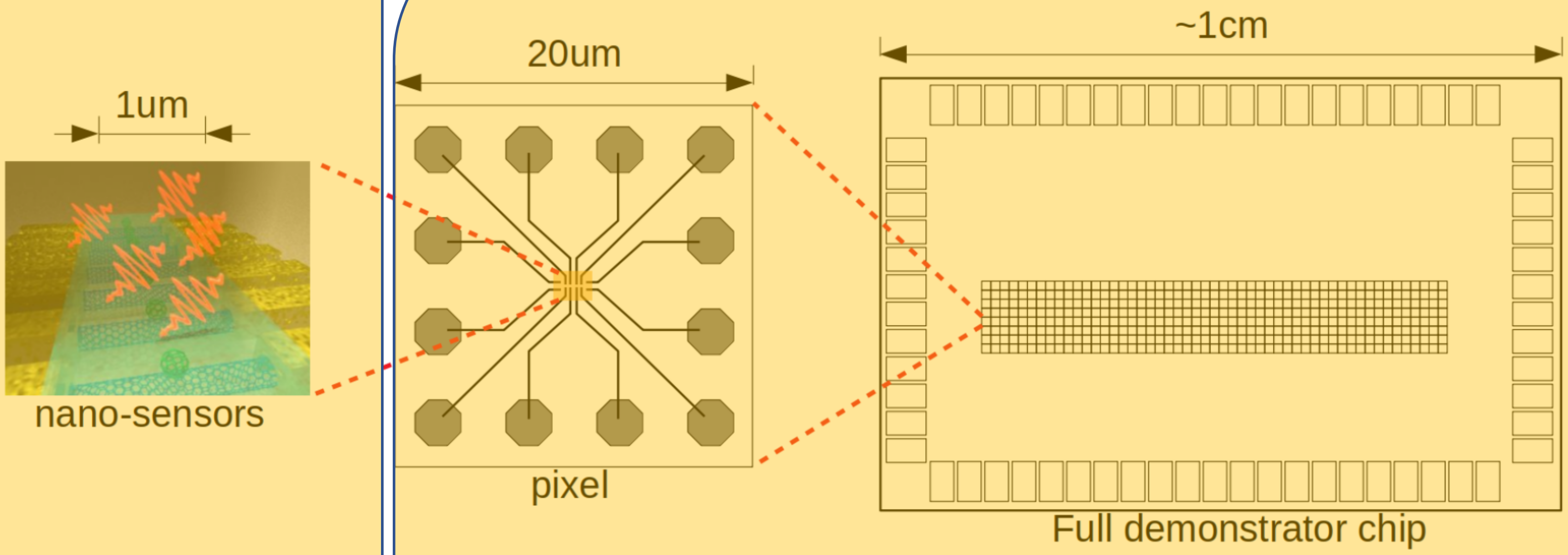
François Léonard

-High efficiency
-Low jitter
-High frequency resolution

https://www.nature.com/articles/s42005-023-01193-1

Single photon sensor with color resolution

Durham Smith

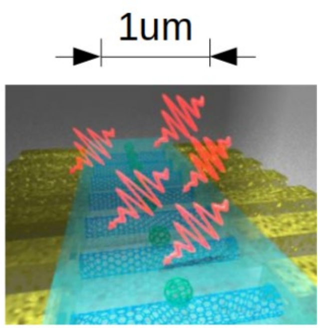


1) Design & assembly of photon transducers

2) Scalable integration of transducers with CMOS

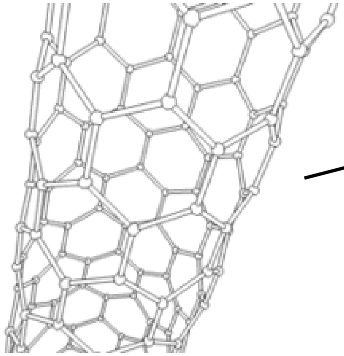
Lin Du

Yunjeong Park

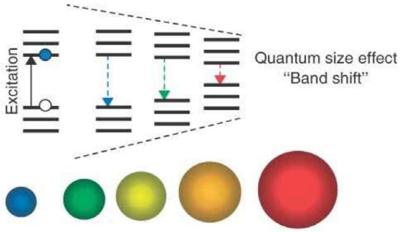


nano-sensors

Design & assembly of photon transducers



1. Carbon nanotubes



2. Quantum dots

Ballistic carbon nanotube field-effect transistors

Ali Javey[1], Jing Guo[2], Qian Wang[1], Mark Lundstrom[2] & Hongjie Dai[1]

[1]*Department of Chemistry, Stanford University, California 94305, USA*
[2]*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA*

A common feature of the single-walled carbon-nanotube field-effect transistors fabricated to date has been the presence of a Schottky barrier at the nanotube–metal junctions[1–3]. These energy barriers severely limit transistor conductance in the 'ON' state, and reduce the current delivery capability—a key determinant of device performance. Here we show that contacting semiconducting single-walled nanotubes by palladium, a noble metal with high work function and good wetting interactions with nanotubes, greatly reduces or eliminates the barriers for transport through the valence band of nanotubes. *In situ* modification of the electrode work function by hydrogen is carried out to shed light on the nature of the contacts. With Pd contacts, the 'ON' states of semiconducting nanotubes can behave like ohmically contacted ballistic metallic tubes, exhibiting room-temperature conductance near the ballistic transport limit of $4e^2/h$ (refs 4–6), high current-carrying capability (~25 μA per tube), and Fabry–Perot interferences[5] at low temperatures. Under high voltage operation, the current saturation appears to be set by backscattering of the charge carriers by optical phonons. High-performance ballistic nanotube field-effect transistors with zero or slightly negative Schottky barriers are thus realized.

Transparent electrical contacts made to metallic single-walled carbon nanotubes (SWNTs) have revealed them to be ballistic conductors that exhibit two units of quantum conductance $4e^2/h$ ($R_Q = h/4e^2 = 6.5\,k\Omega$)[4–6]. Carrier transport through the valence and conduction bands of a high-quality semiconducting SWNT could also be ballistic, presenting an opportunity to realize ballistic

monotonically increases as temperature T decreases to ~50 K (Fig. 1d), below which pronounced oscillations with Fabry-Perot type of interferences[5] appear in the G versus gate voltage (V_{gs}) data

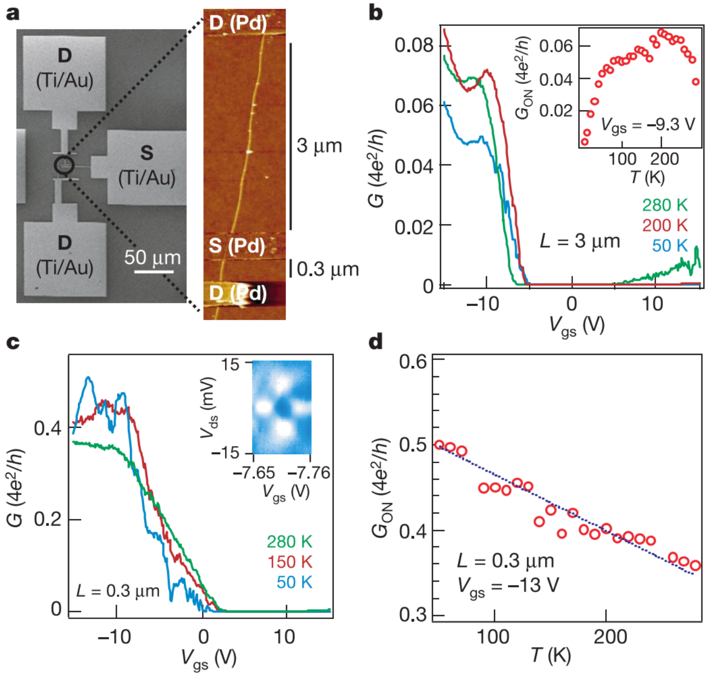
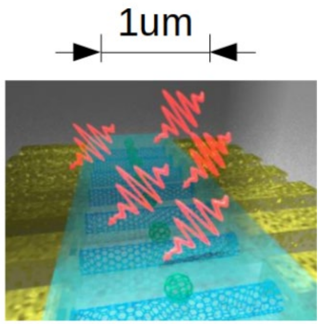
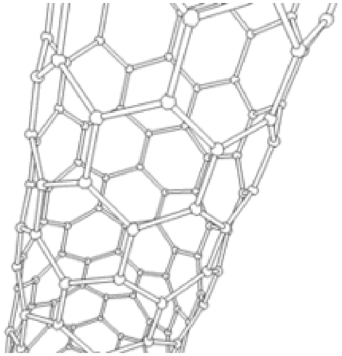


Figure 1 Pd-contacted long ($L = 3\,\mu m$) and short ($L = 300\,nm$) back-gated SWNT devices formed on the same nanotubes on SiO_2/Si. **a**, A scanning electron microscope (SEM) image (left) and atomic force microscope (AFM) image (right) of a representative device. CVD synthesis for SWNTs and device fabrication were as described previously[25,26], except that Pd was used to contact nanotubes. The catalyst used here gave a wide range of nanotube diameters (1.2 – 5 nm)[25]. Ti/Au metal bonding pads were used to connect to the Pd source (S) and drain (D) electrodes. (We note that Pd electrodes tended to be soft and not robust against electrical probing). The devices were annealed in Ar at 225 °C for 10 min after fabrication. The thickness of SiO_2 gate dielectric was $t_{ox} = 500\,nm$, except for the devices in Fig. 4 with $t_{ox} = 67\,nm$. AFM topographic height measurements were used to determine the diameters of SWNTs. The electrical data

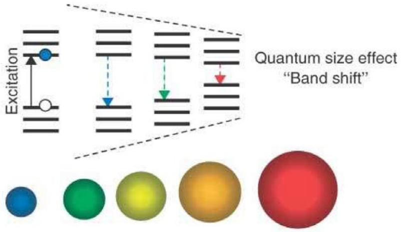


nano-sensors

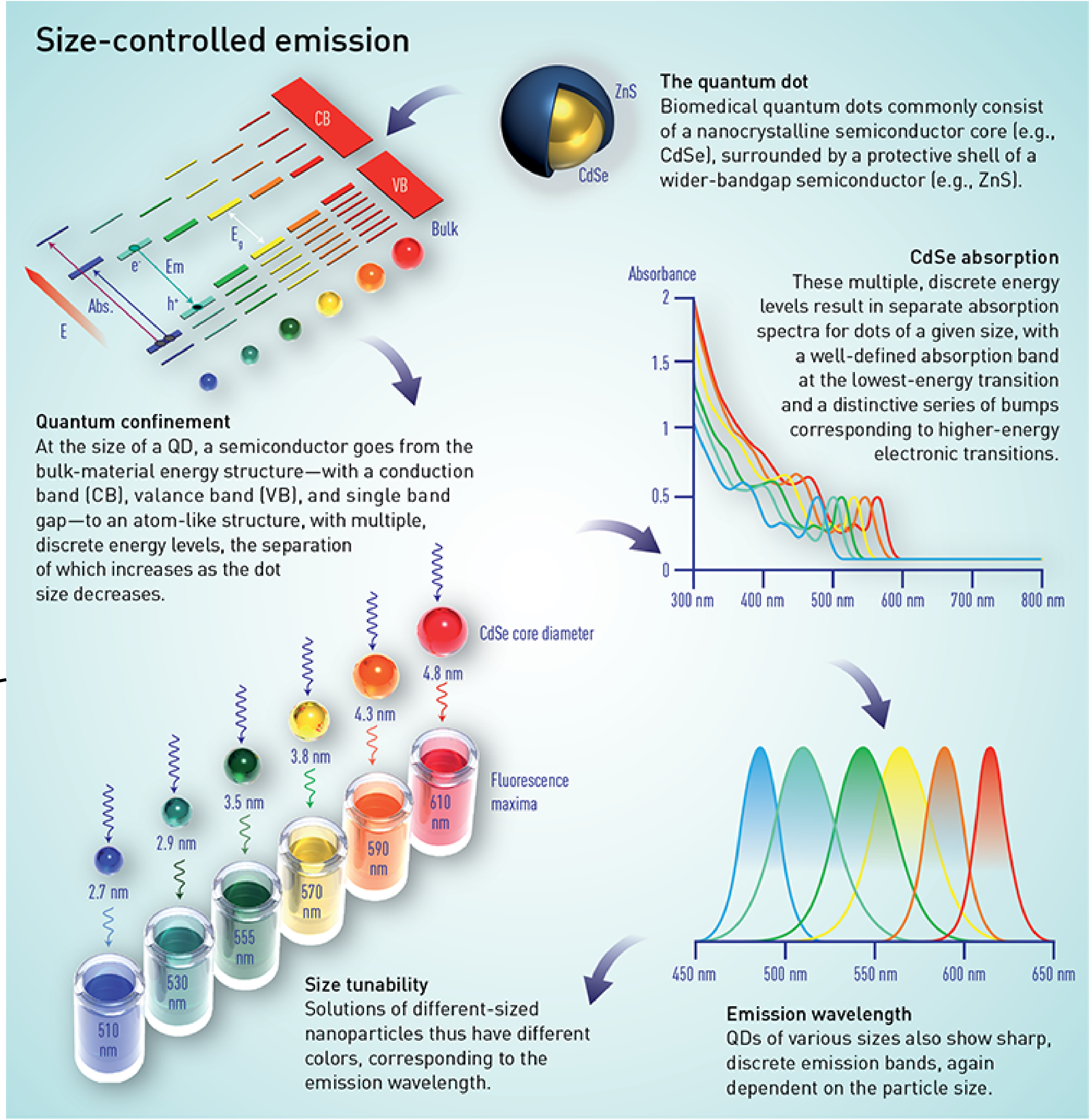
Design & assembly of photon transducers

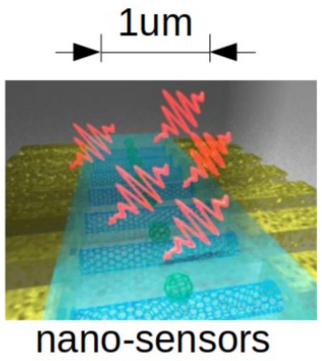


1. Carbon nanotubes

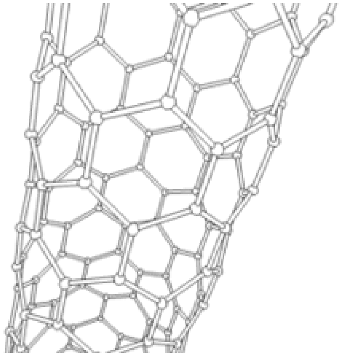


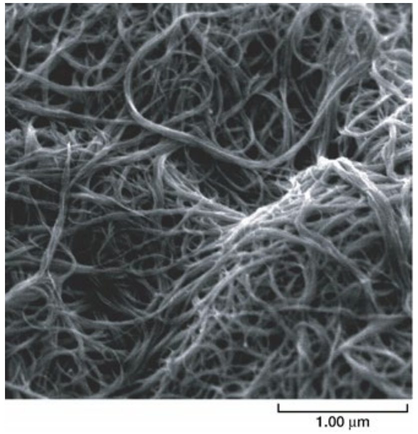
2. Quantum dots



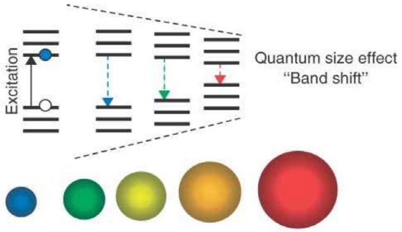


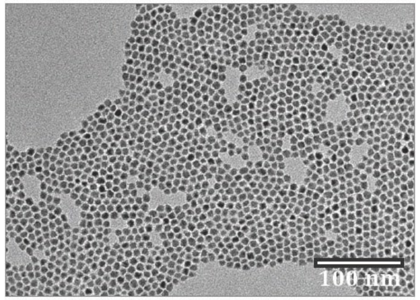
Design & assembly of photon transducers





1. Carbon nanotubes



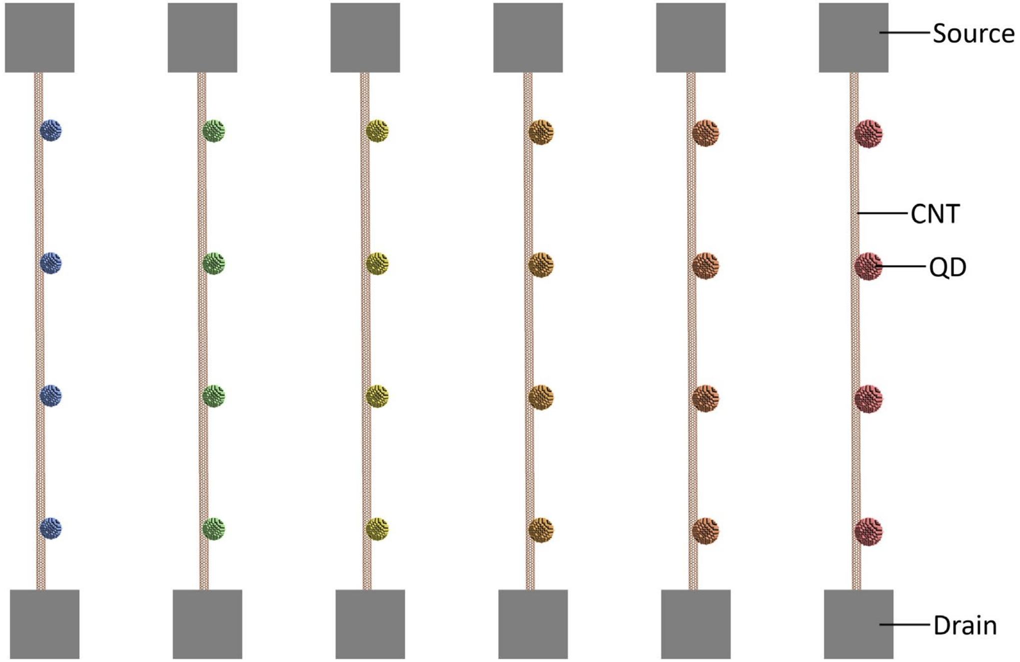


2. Quantum dots

?

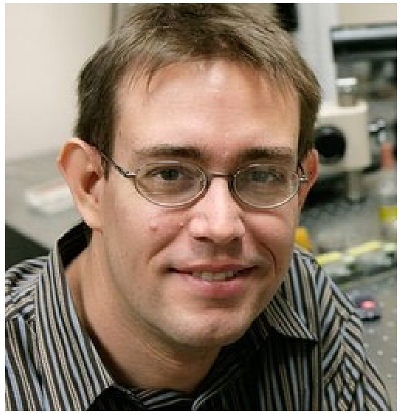
3. DNA!

How can we assemble such an architecture in subwavelength area?

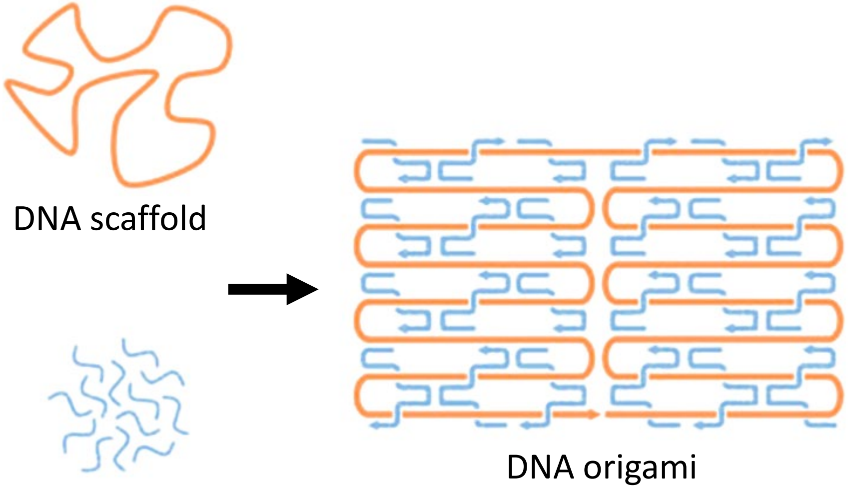


DNA Nanotechnology

DNA origami

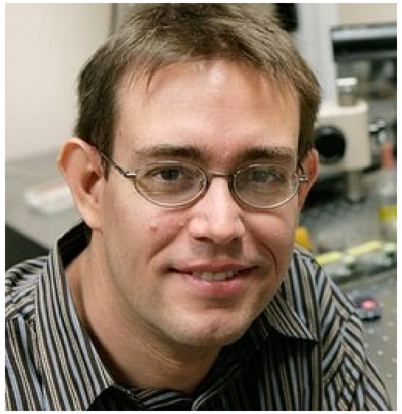


Paul Rothemund

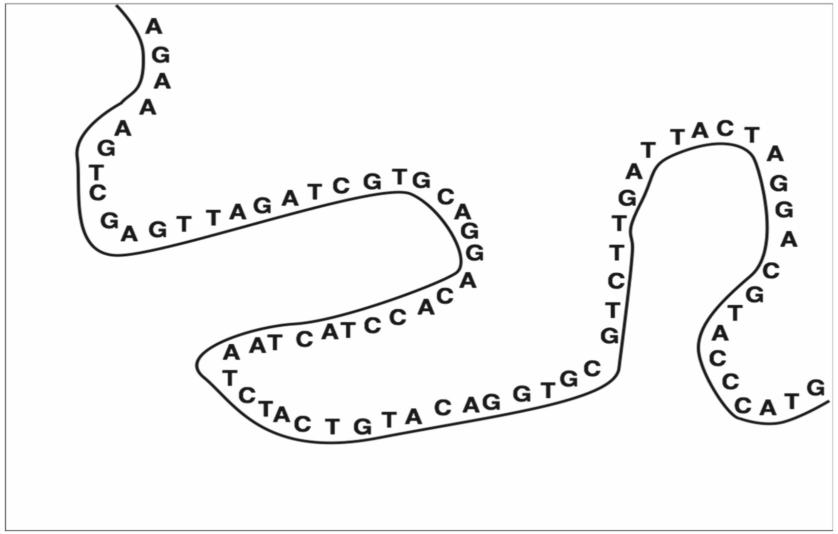


Rothemund, Nature 2006

DNA origami

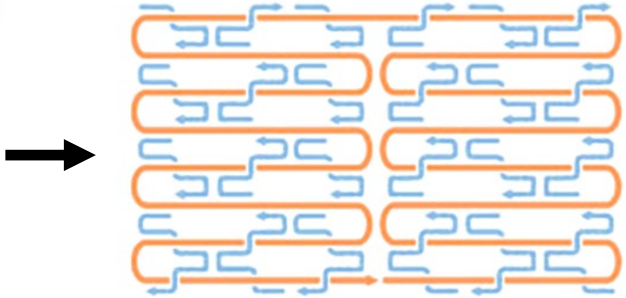


Paul Rothemund

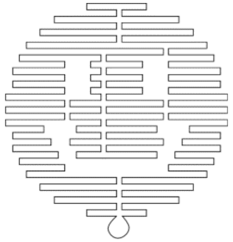


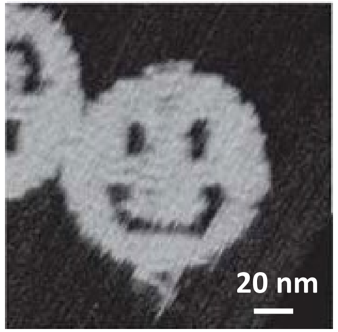
DNA scaffold

Staple strands



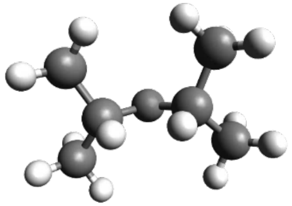
DNA origami

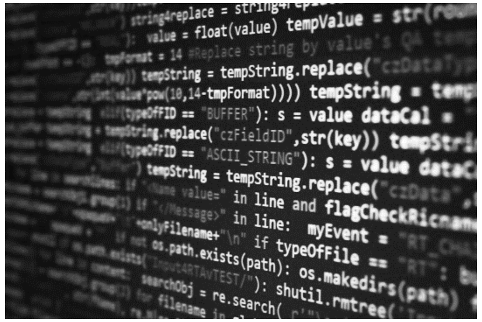


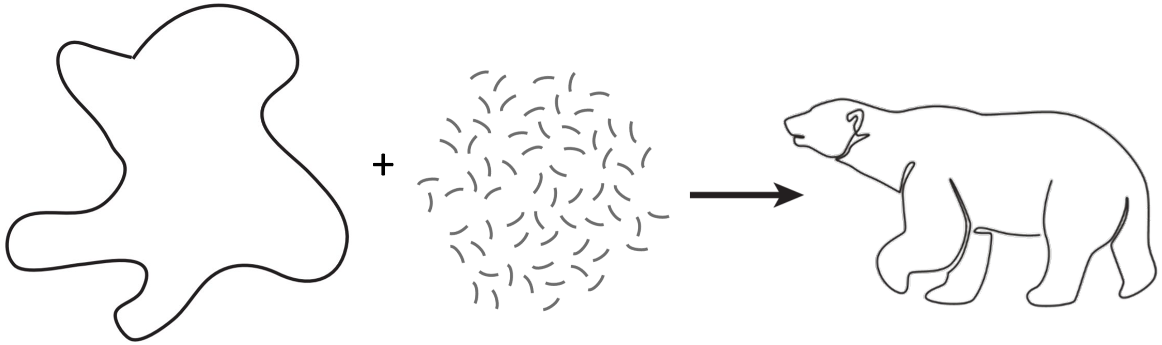


Rothemund, Nature 2006

Endow molecules with a programming language!





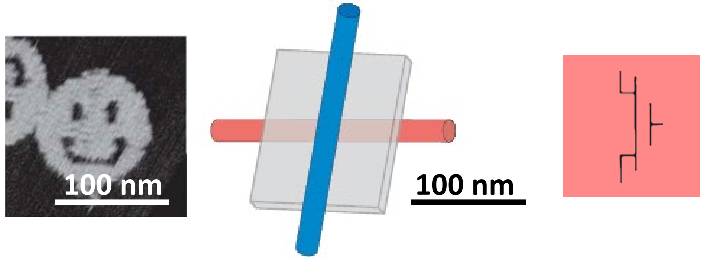


DNA scaffold

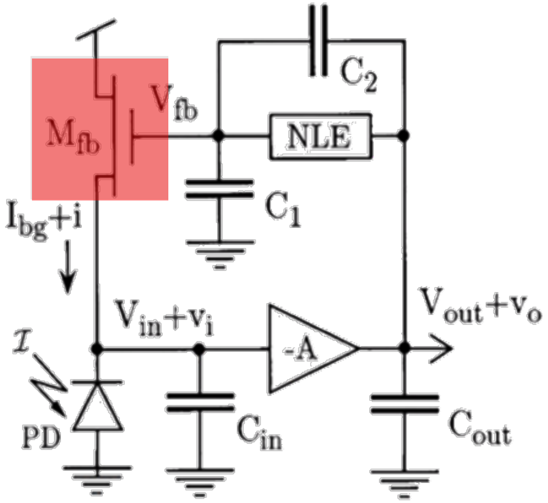
Staples

ATACG….
TTCGA….
GCGAC…

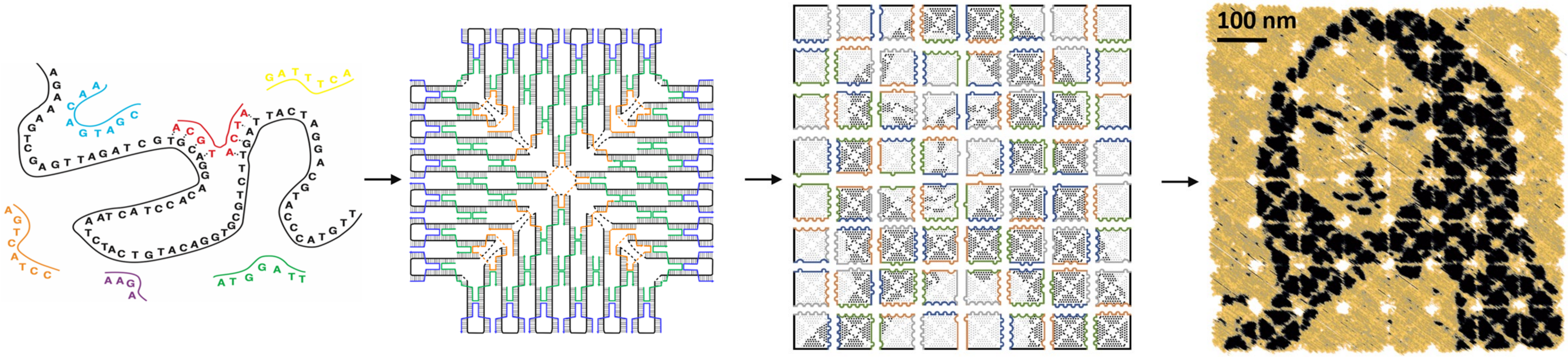
Increasing size of DNA structures



Maune et al, Nat. Nanotechnol. 2010

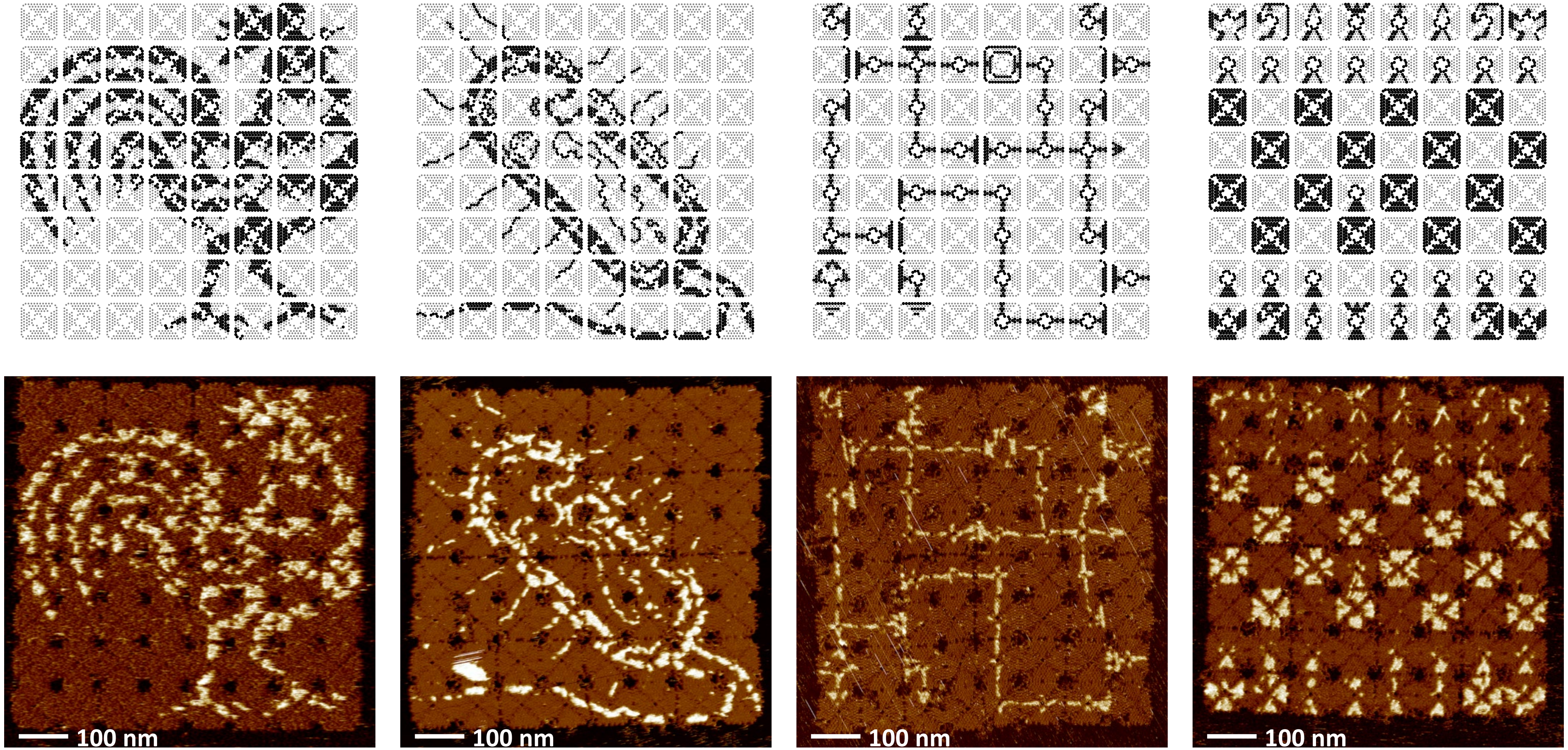


Increasing size of DNA structures

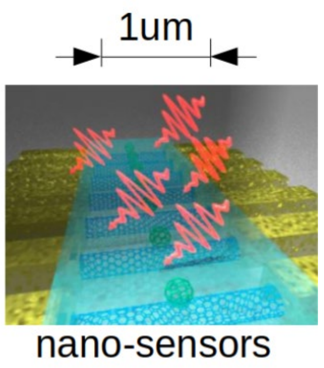


Tikhomirov et al., Nature 2017

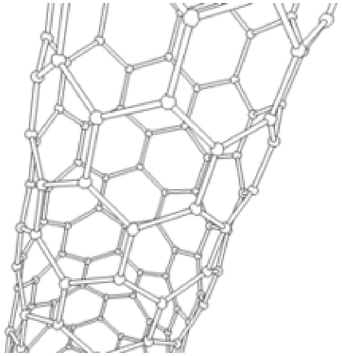
Automated design and experiments

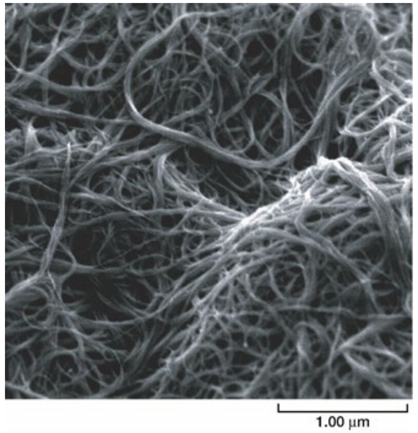


Tikhomirov et al., Nature 2017

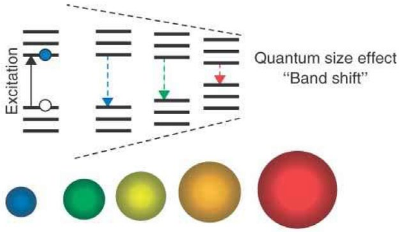


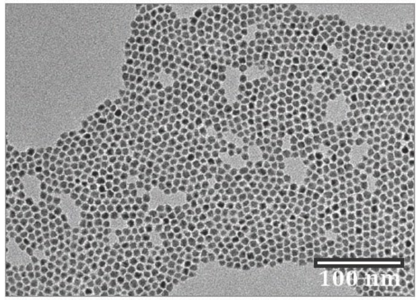
Design & assembly of photon transducers



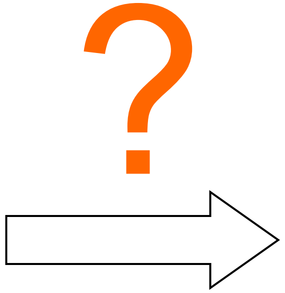


1. Carbon nanotubes

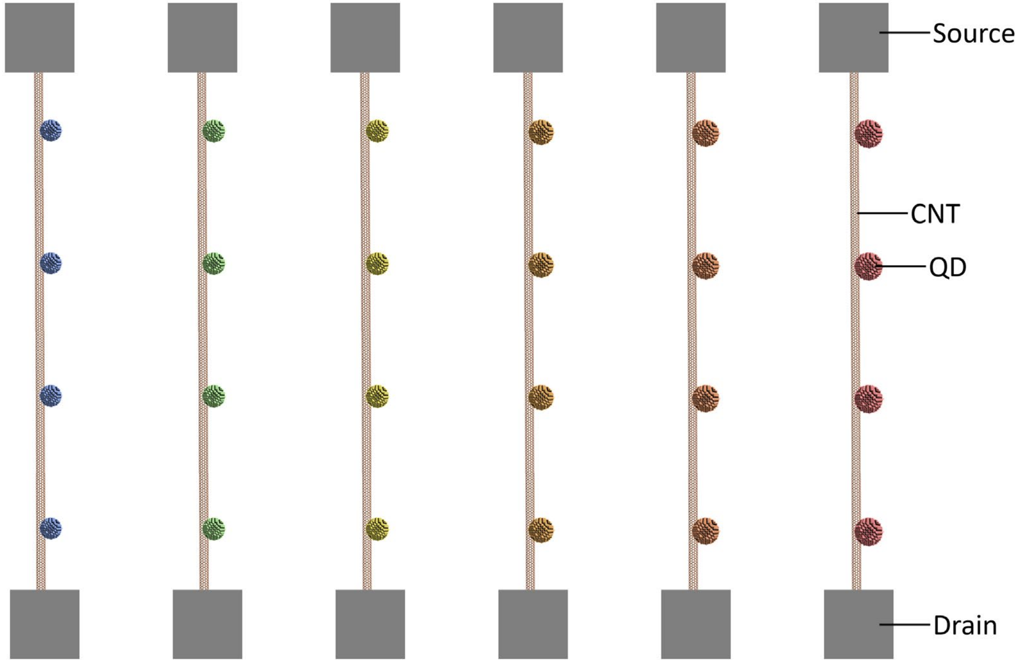


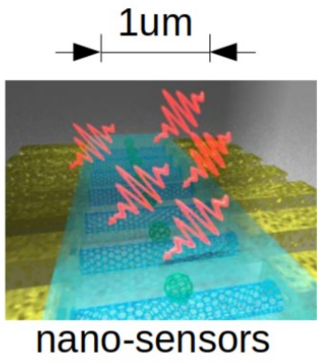


2. Quantum dots

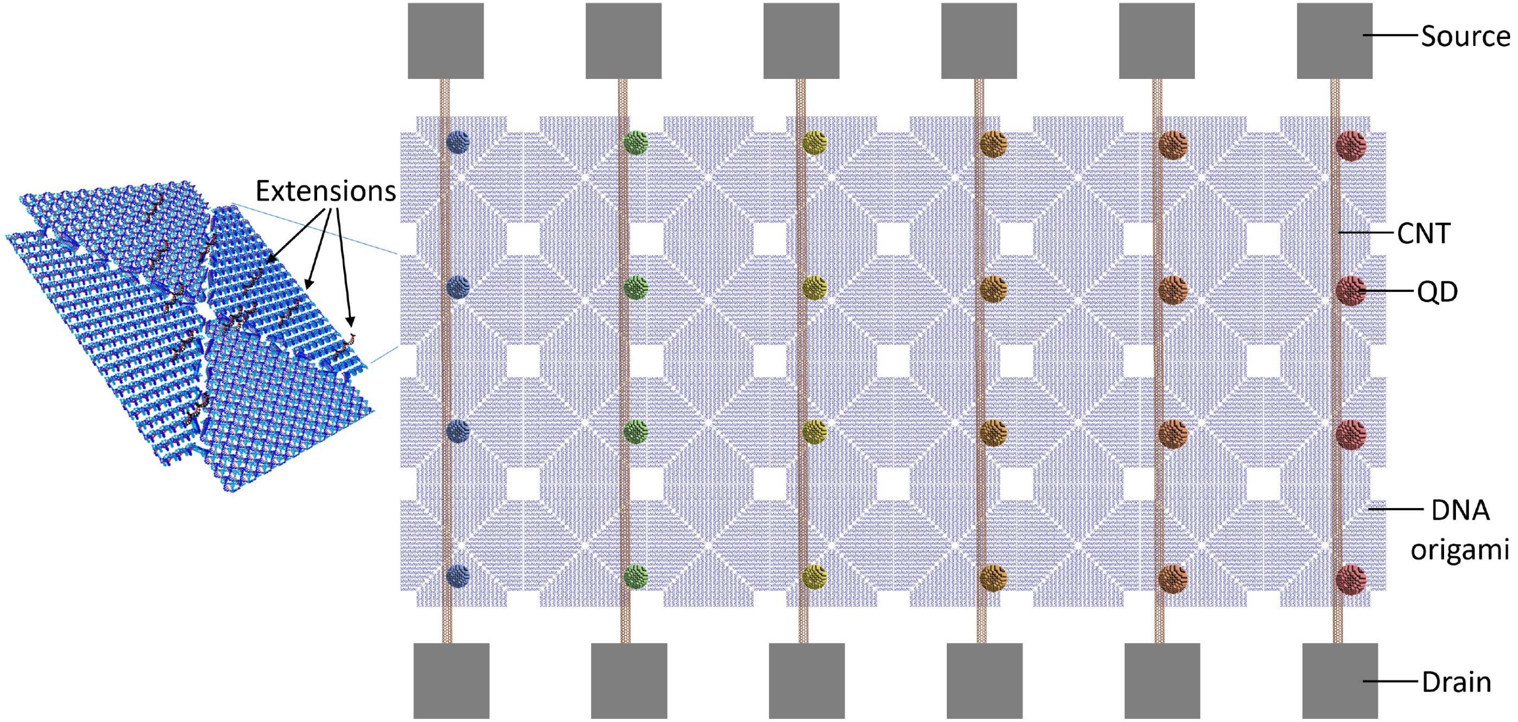


3. DNA





Design & assembly of photon transducers



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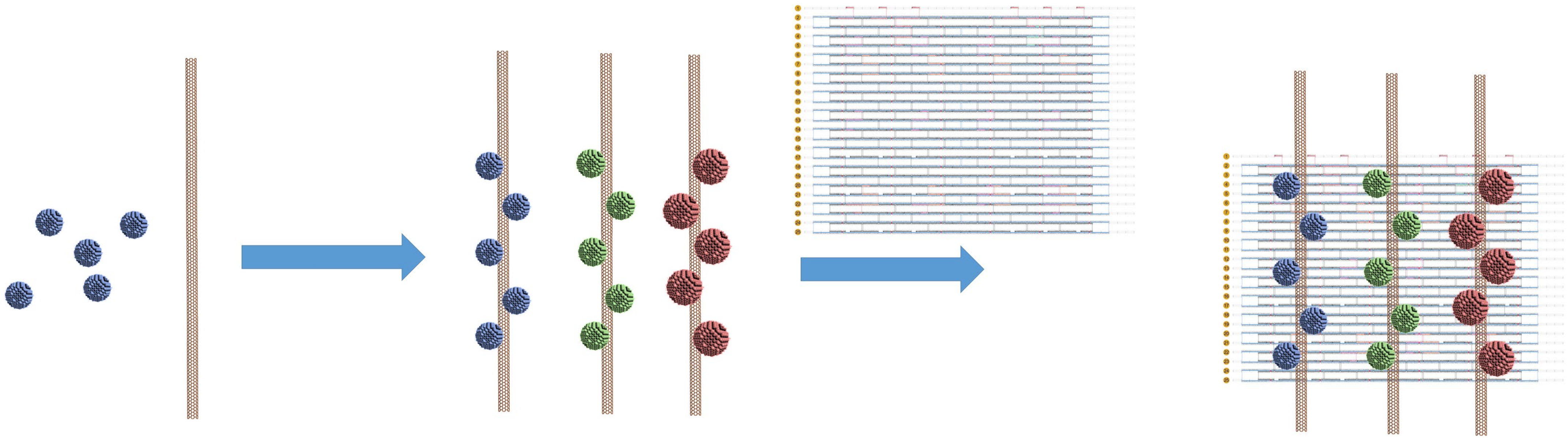
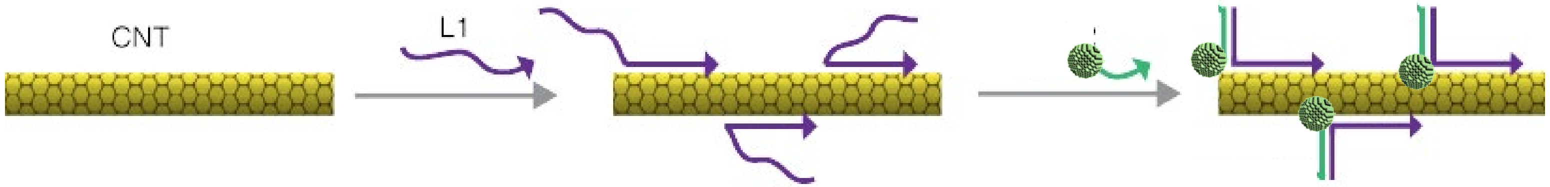


Design & assembly of photon transducers



Durham Smith

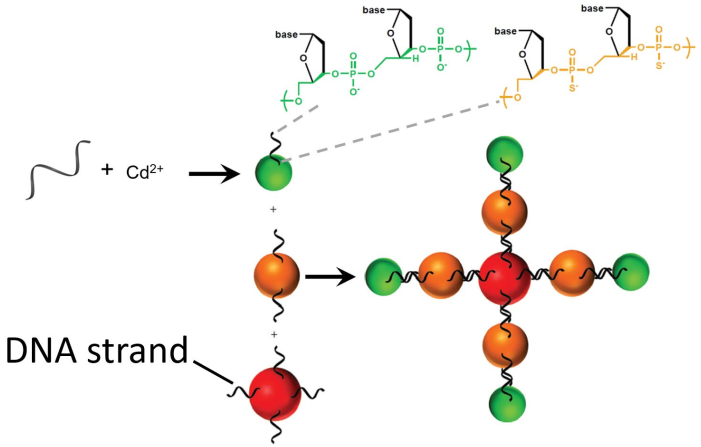
S1: 5'–GATGCGAGGCTATTCTGTGTGTGTGTGTGTGTGTGTGTGTGTGTGTGTGTGTGTGT–3'

binds to CNT

S2: 5'–G*G*T*T*T*G*G*T*G*G*AGAATAGCCTCGCATC–3'

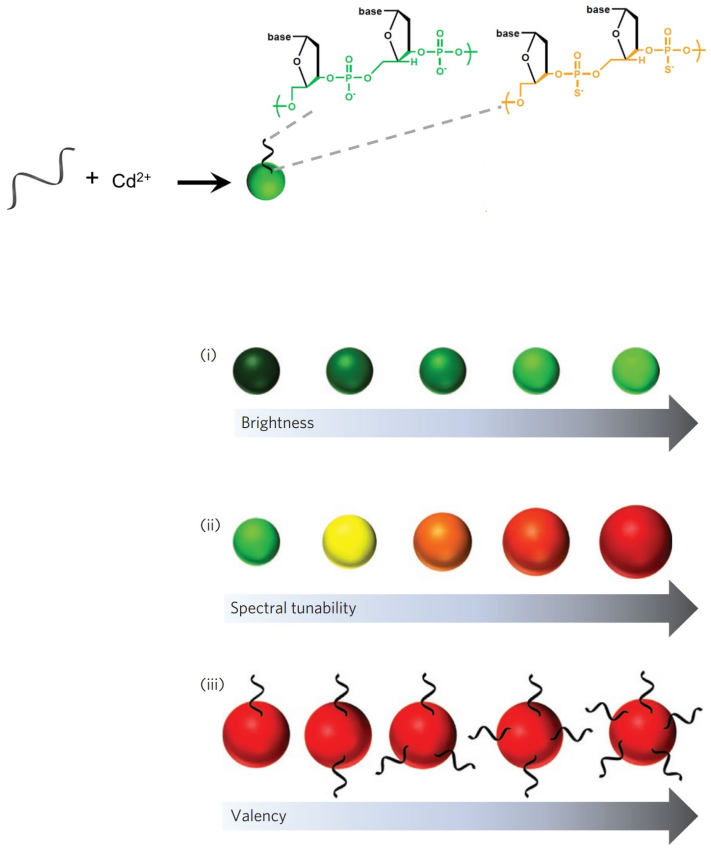
binds to QD

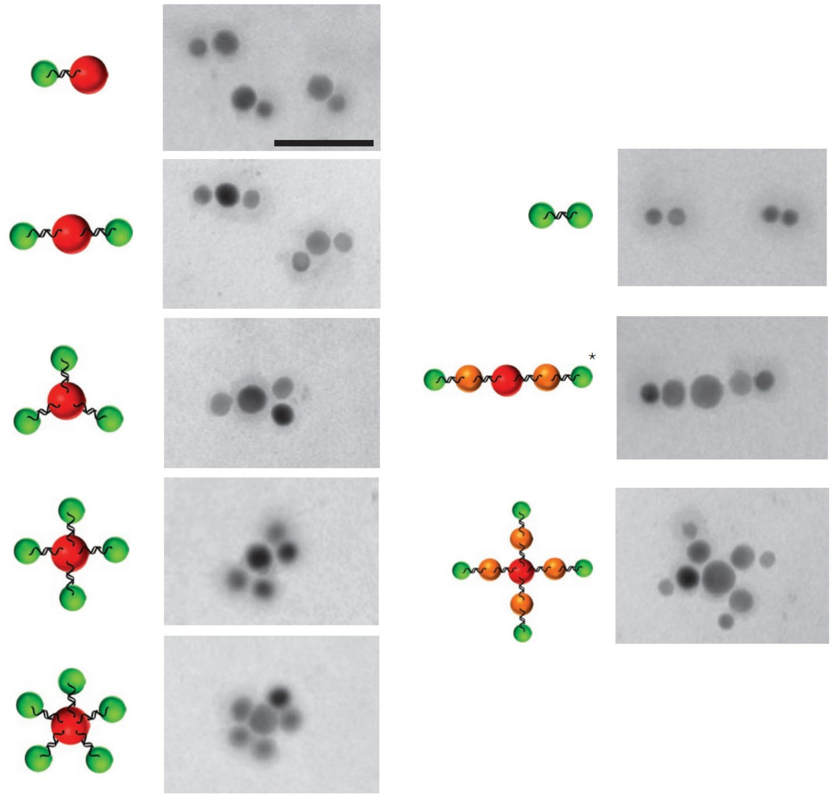
G* - phosphorothioate G nucleotide



Tikhomirov et al, Nature Nanotechnology 2011

Design & assembly of photon transducers

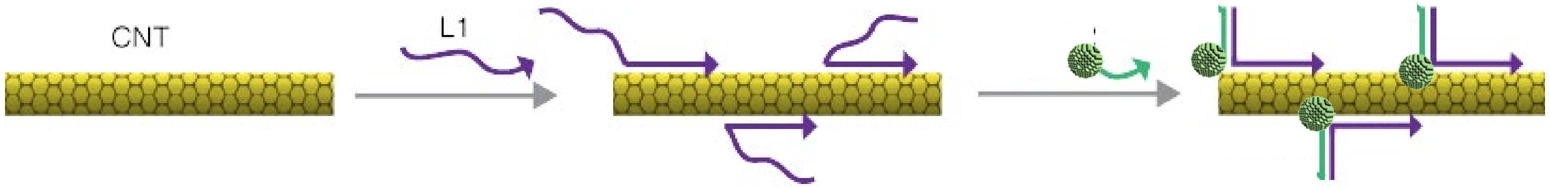


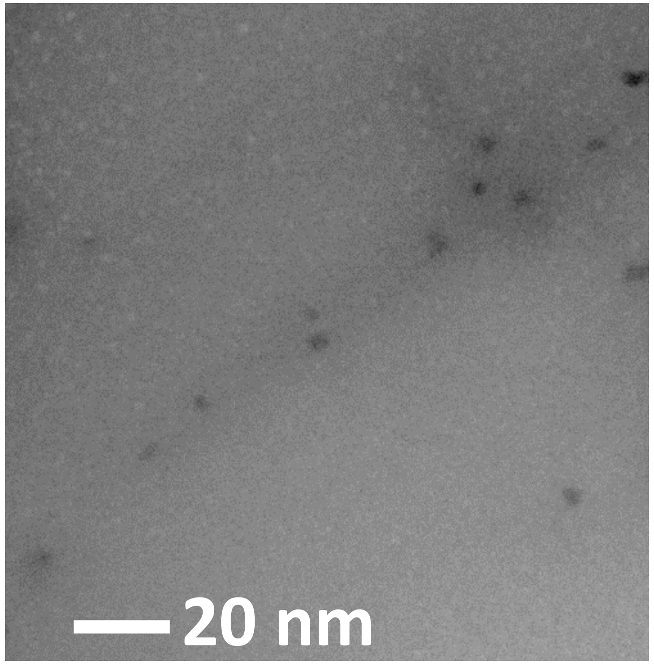


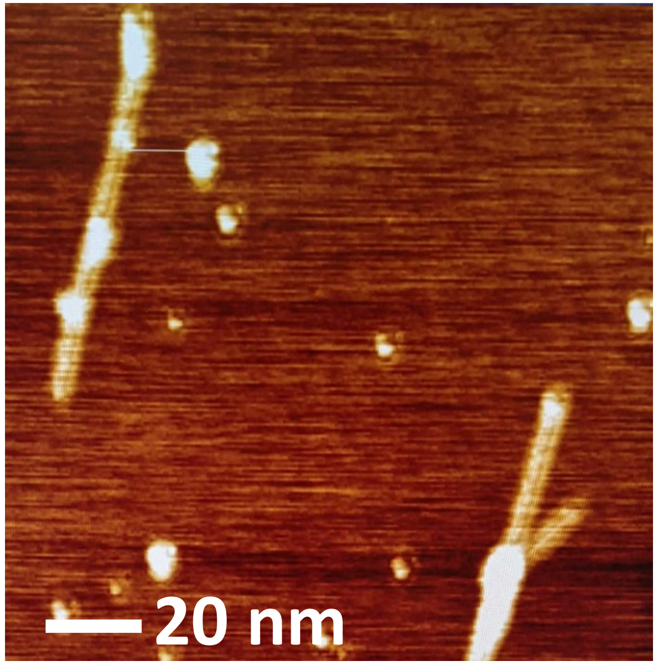
Tikhomirov et al, Nature Nanotechnology 2011

Self-assembly carbon nanotube-quantum dot sensors

Durham Smith

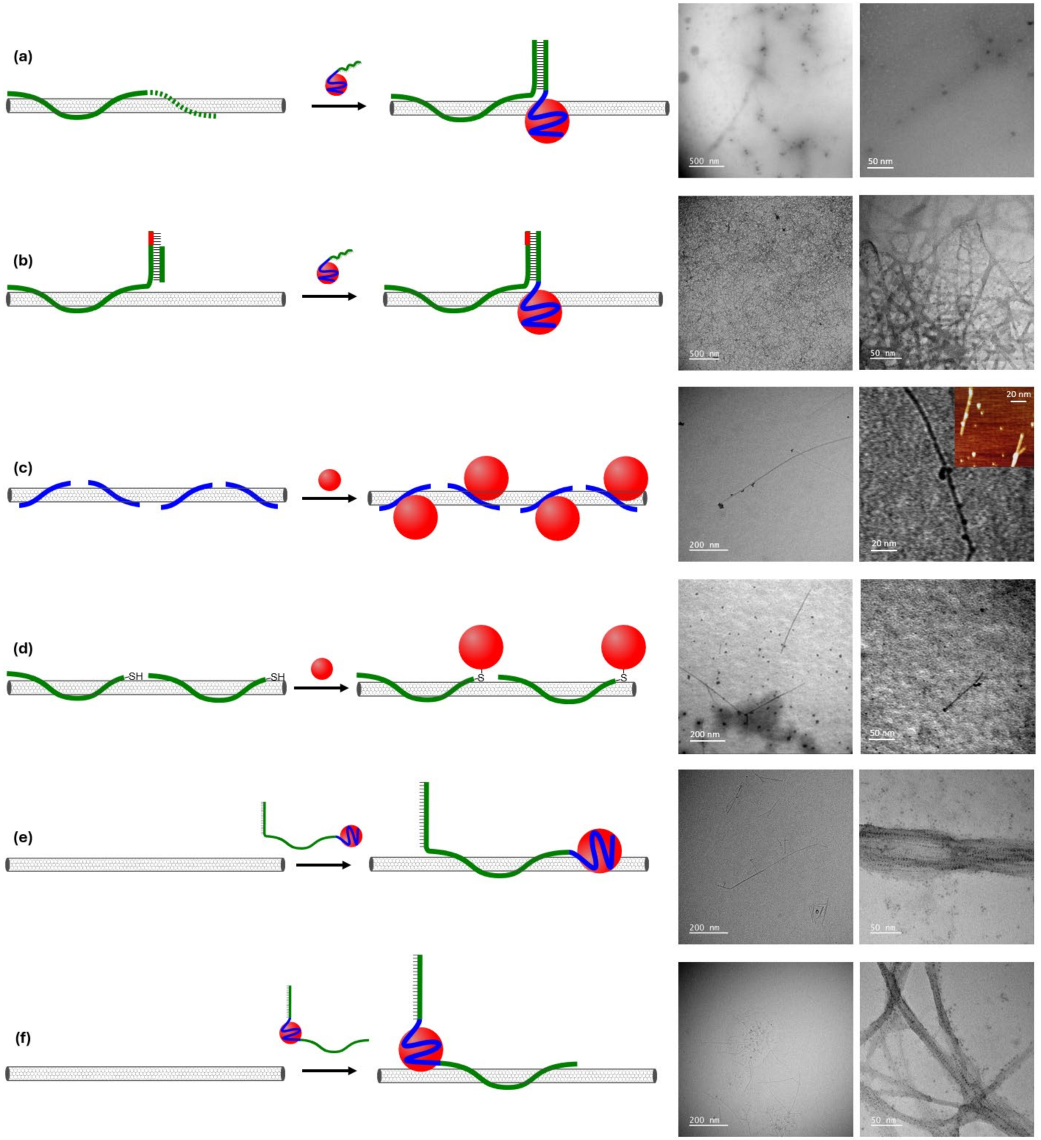






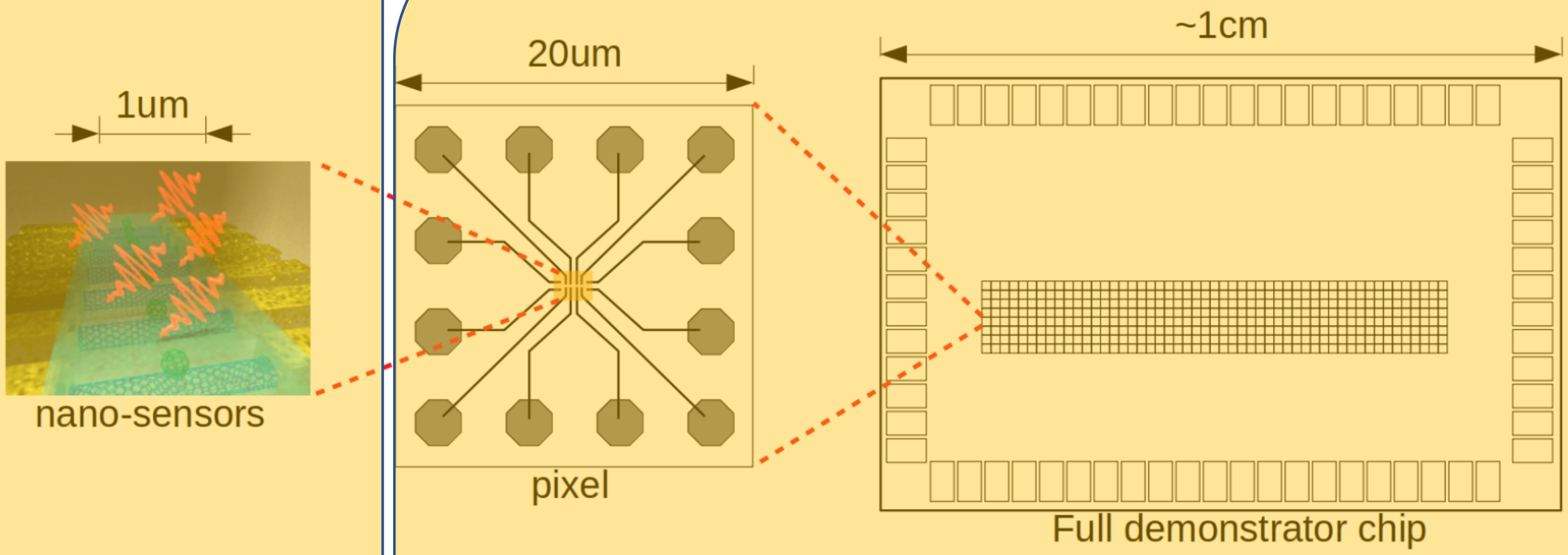
Self-assembly carbon nanotube-quantum dot sensors

Durham Smith



Single photon sensor with color resolution

Durham Smith

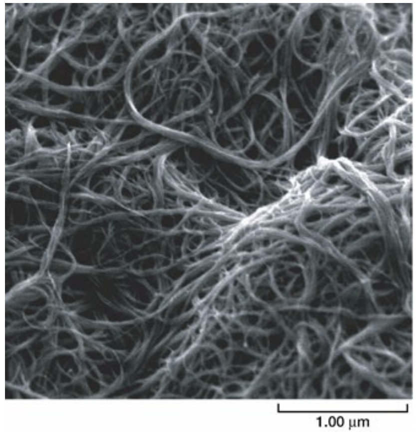


1) Design & assembly of photon transducers

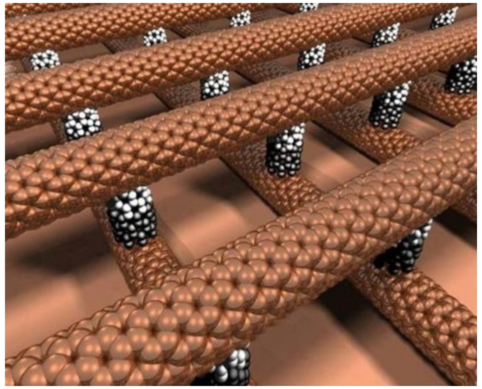
2) Scalable integration of transducers with CMOS

Yunjeong Park

Towards ideal nanotechnology: Chemistry

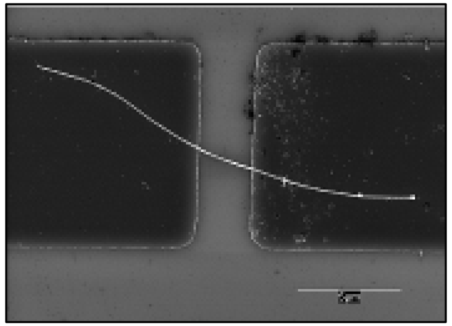


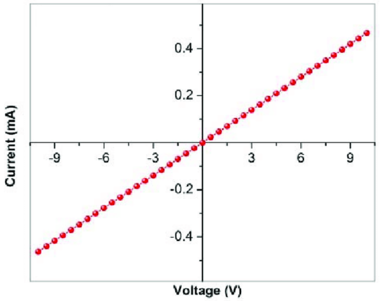
?



Challenge: How to precisely assemble structures?

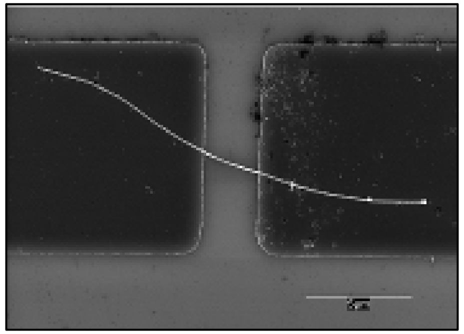
“Spray and Pray”





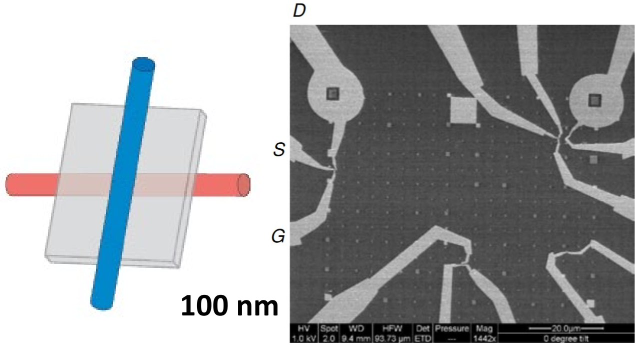
Current approaches to integrating top-down and bottom-up components are not scalable

1. "Spray and Pray"



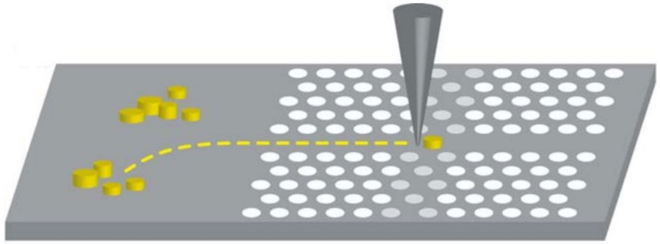
Tikhomirov et al, JOC 2008

2. "Hunt & Peck & Connect"



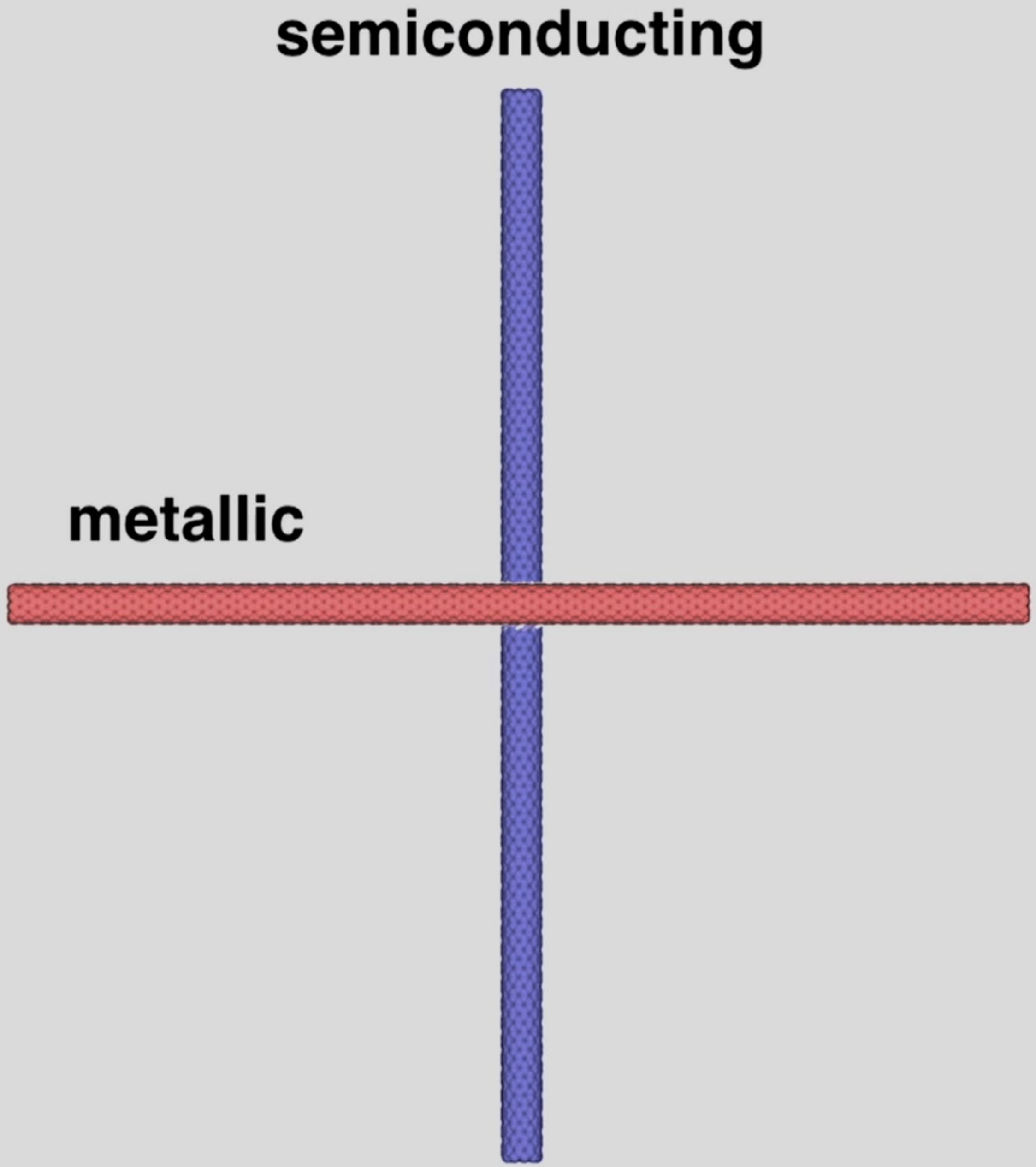
Maune et al, Nat. Nanotechnol. 2010

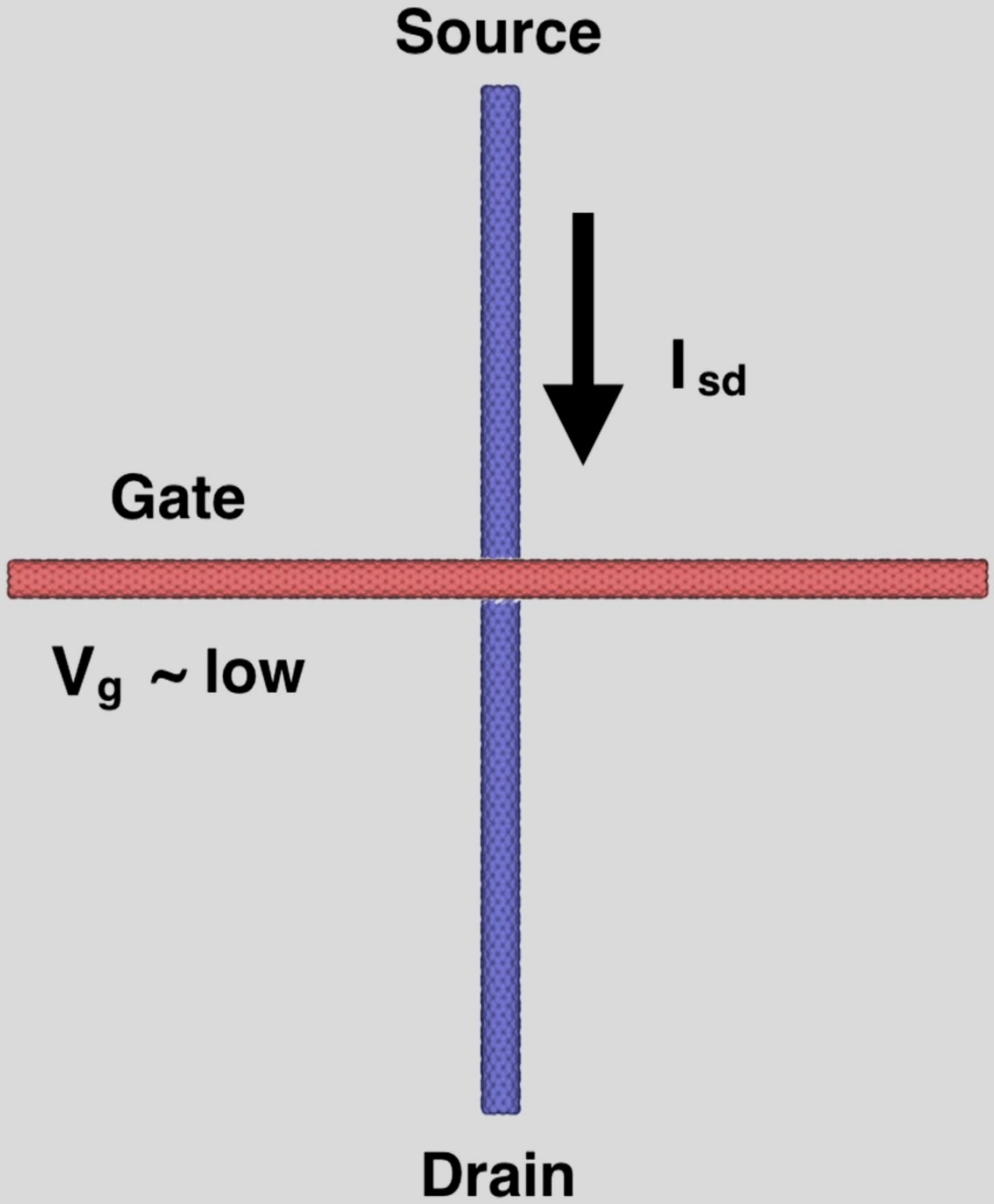
3. Dip Pen Deposition



Barth et al, Optic Letters, 2009

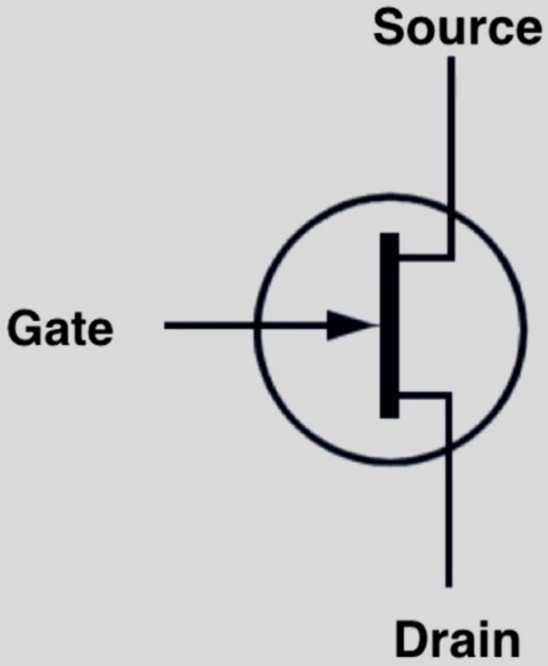
carbon nanotube

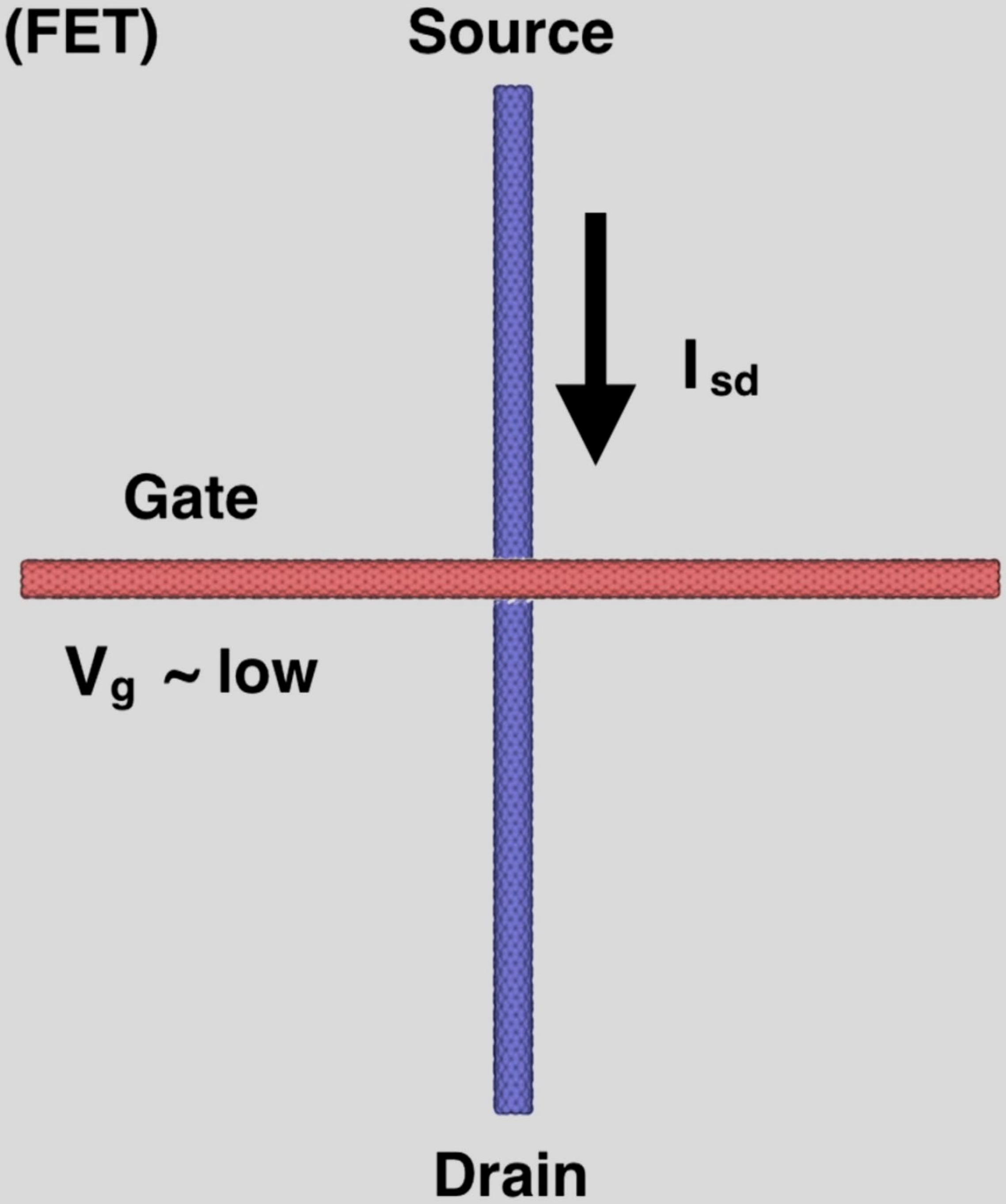

semiconducting
metallic



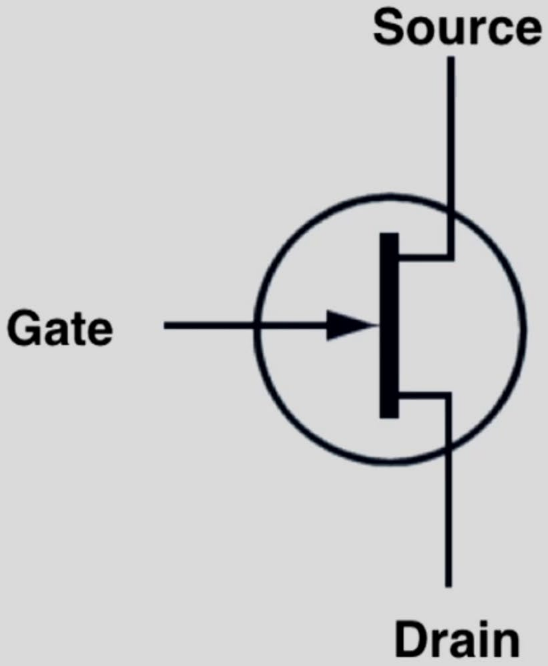
Source
I sd
Gate
V g ~ low
Drain

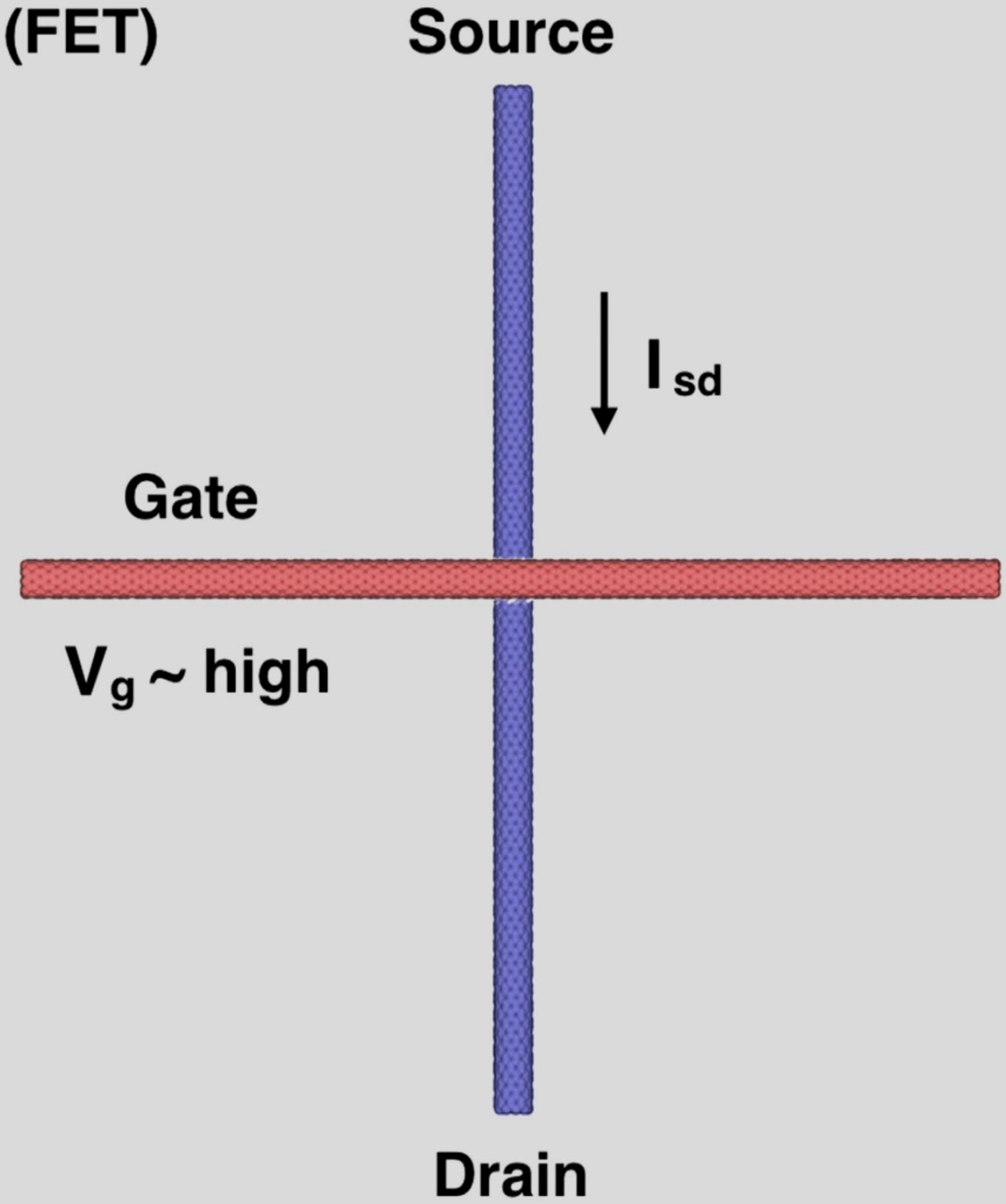
Field Effect Transistor (FET)

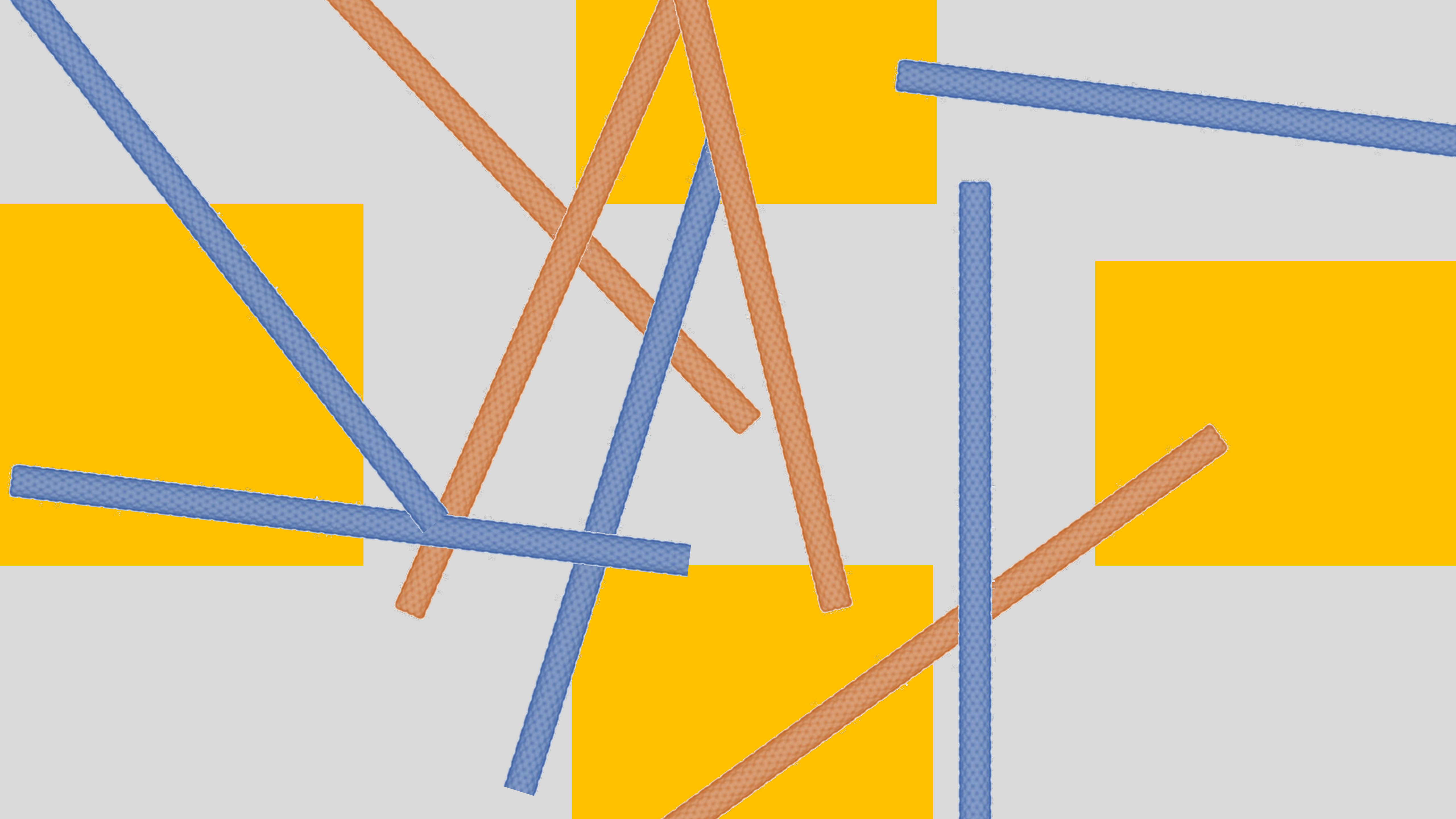


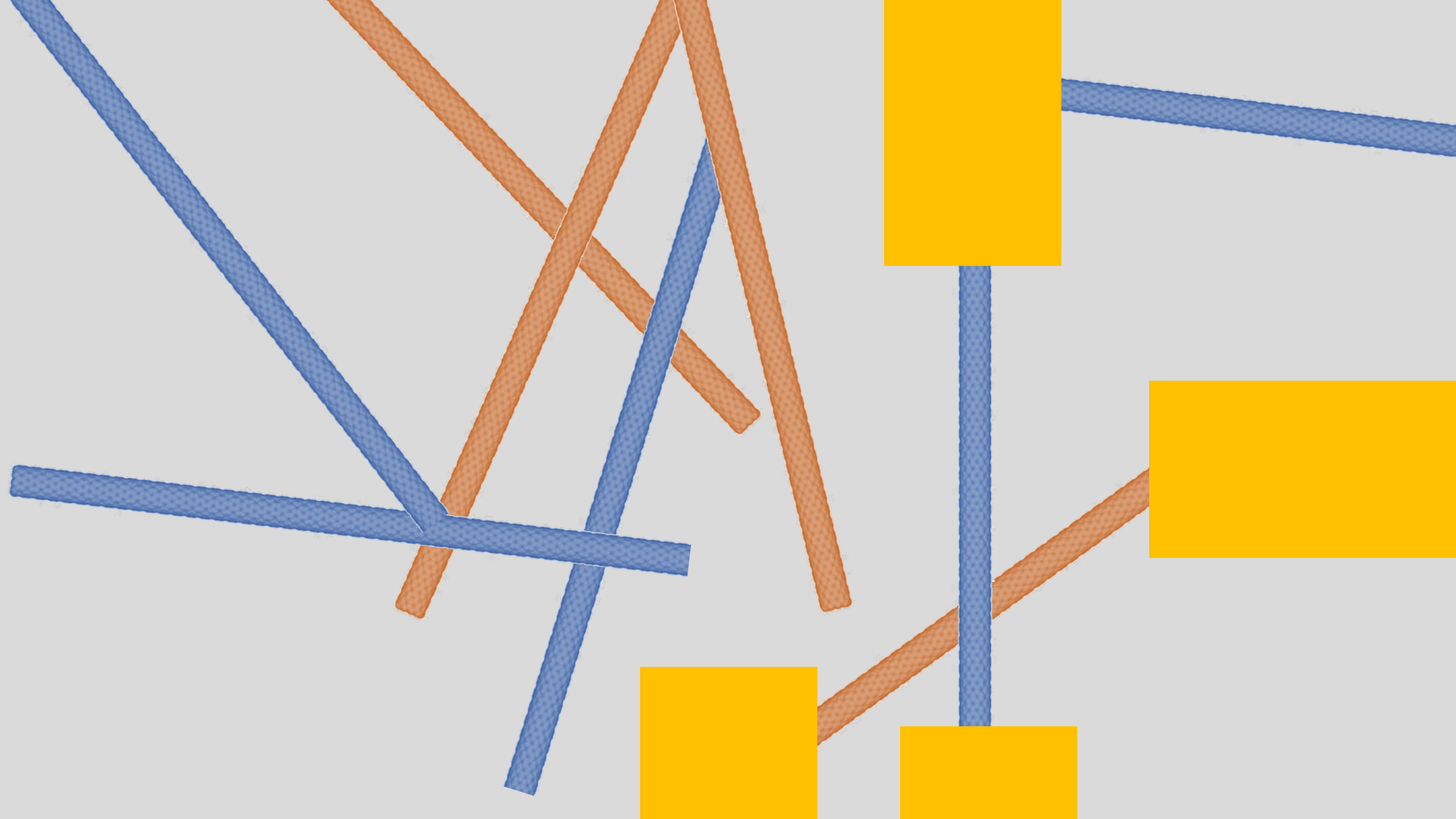


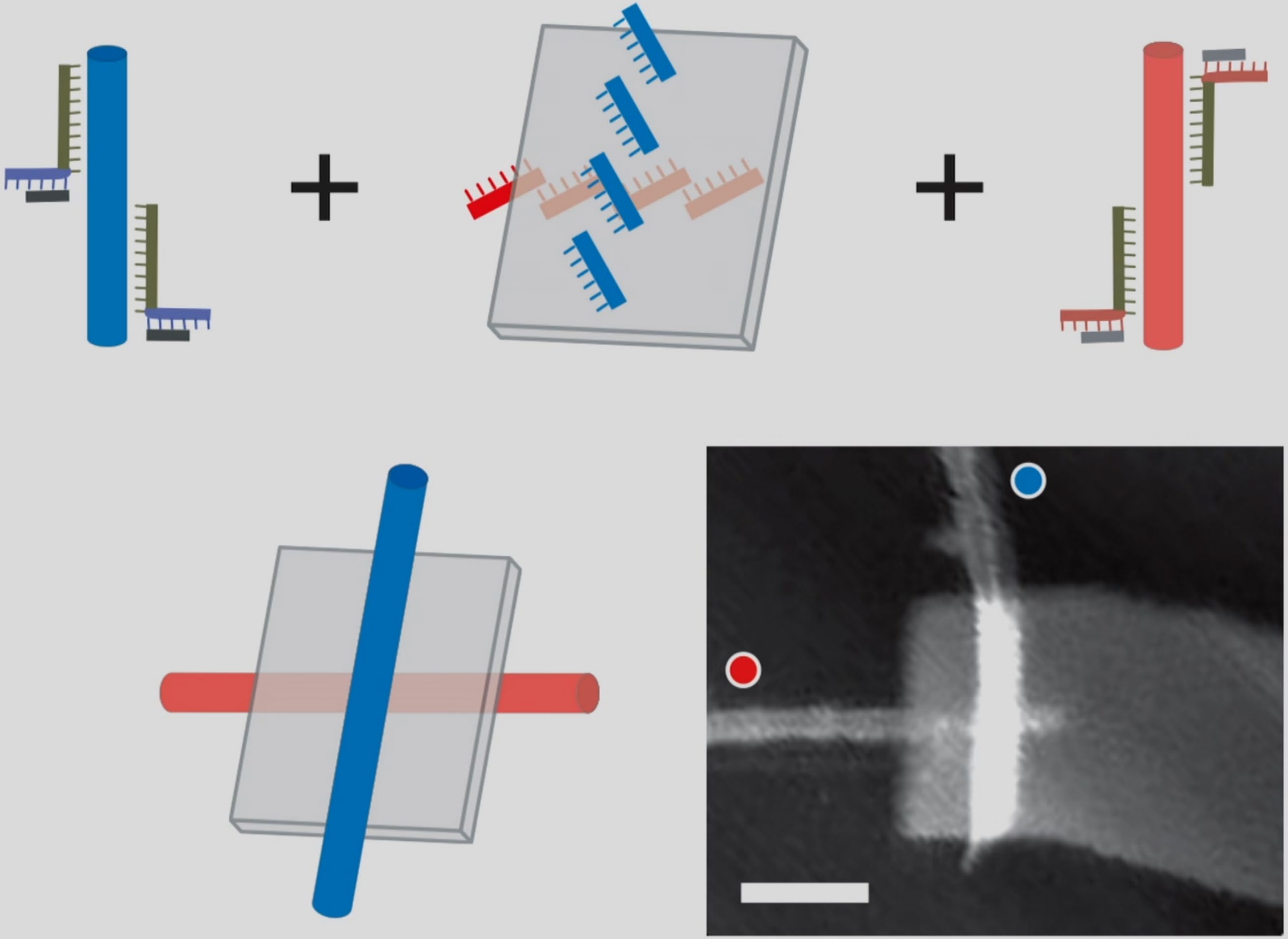
Field Effect Transistor (FET)

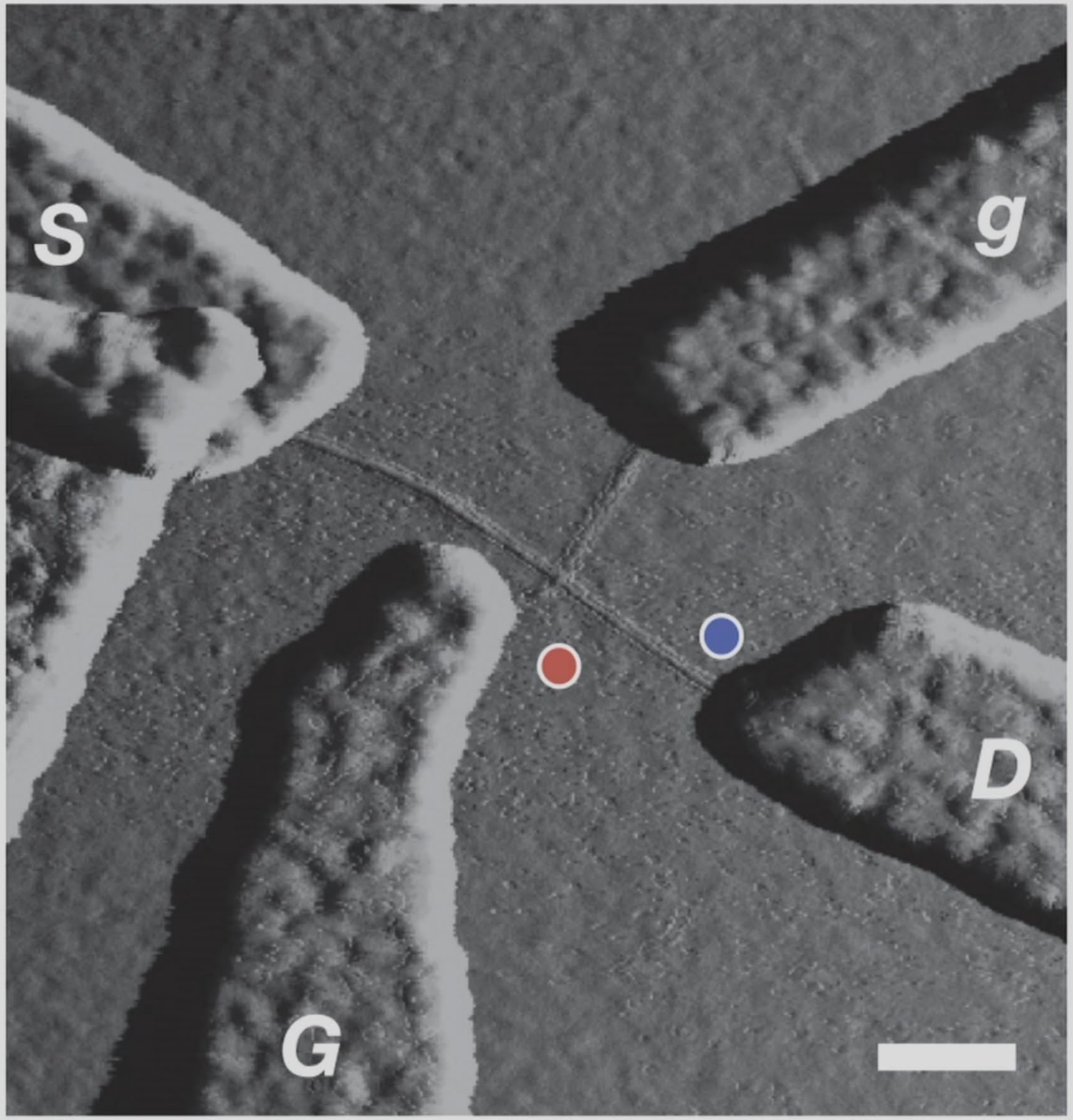


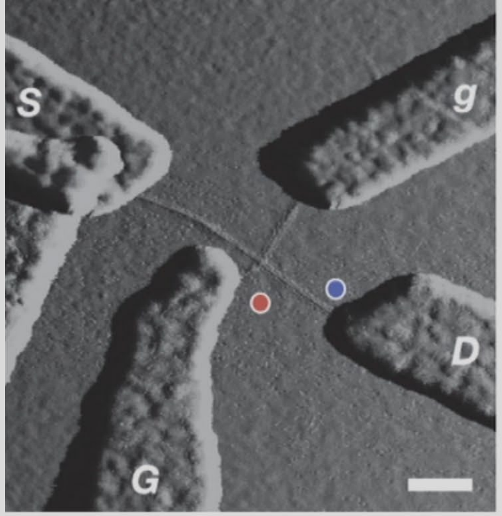


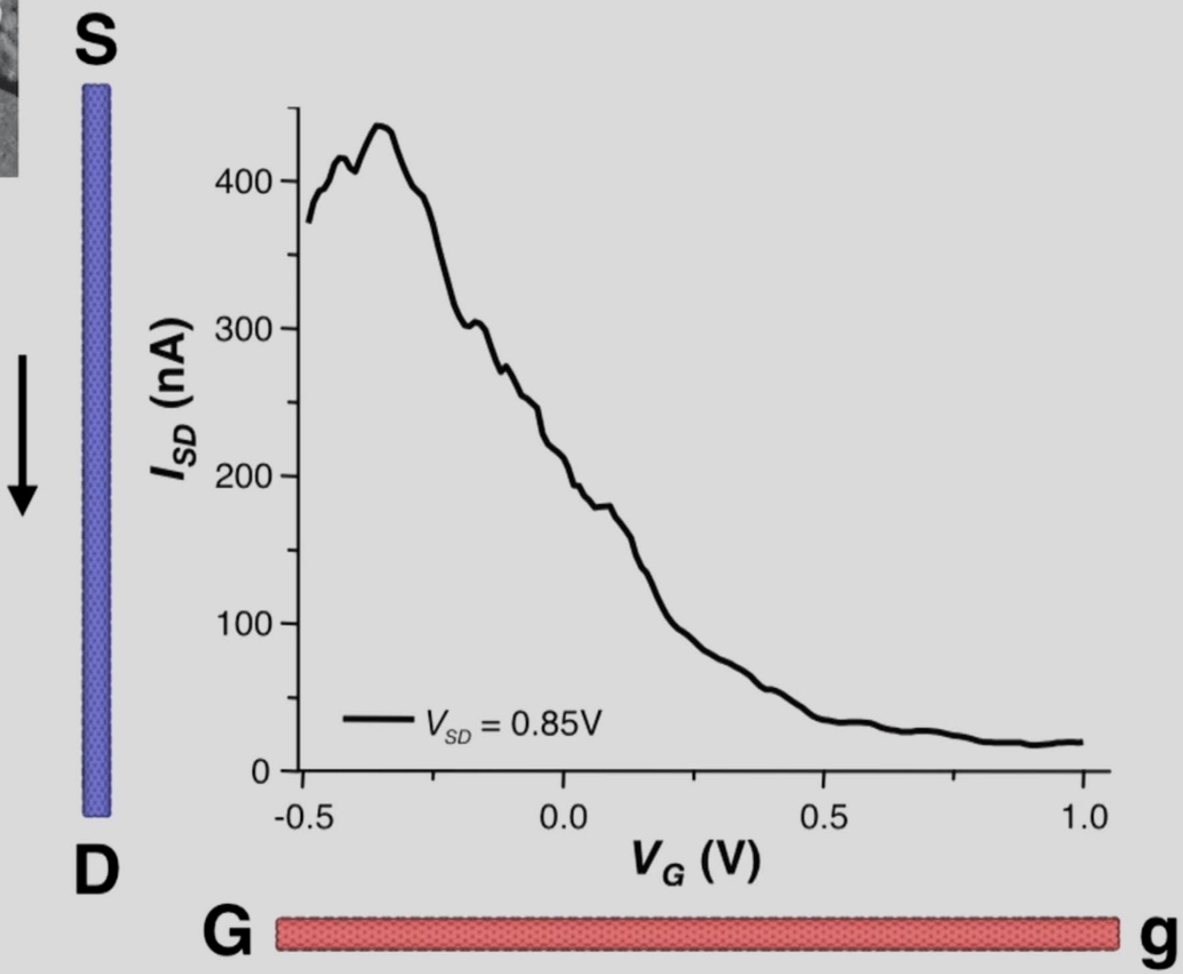


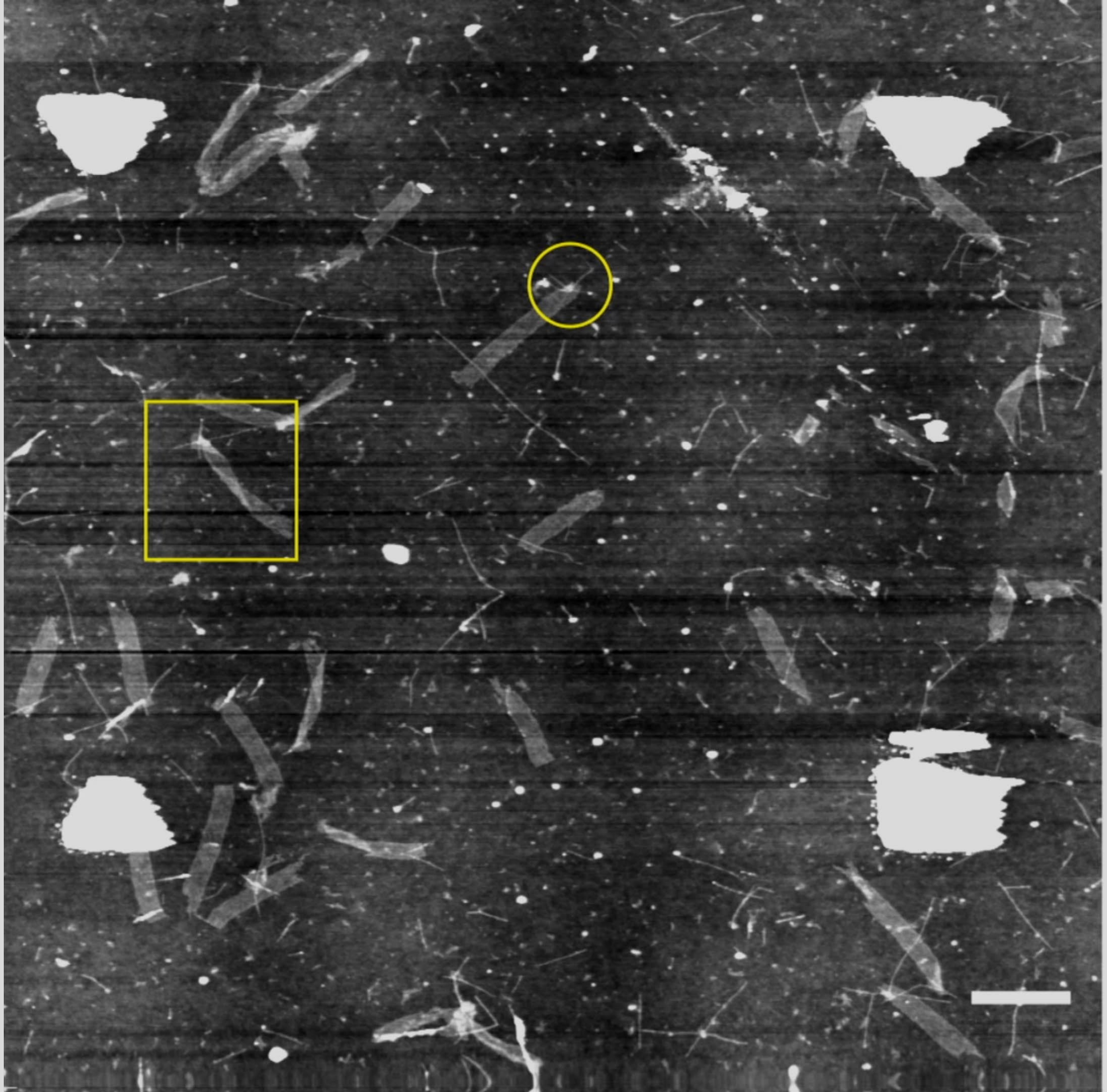





S
g
D
G


S
g
D
G


S
D
G
g
I_{SD} (nA)
V_G (V)
V_{SD} = 0.85V
0
100
200
300
400
-0.5
0.0
0.5
1.0

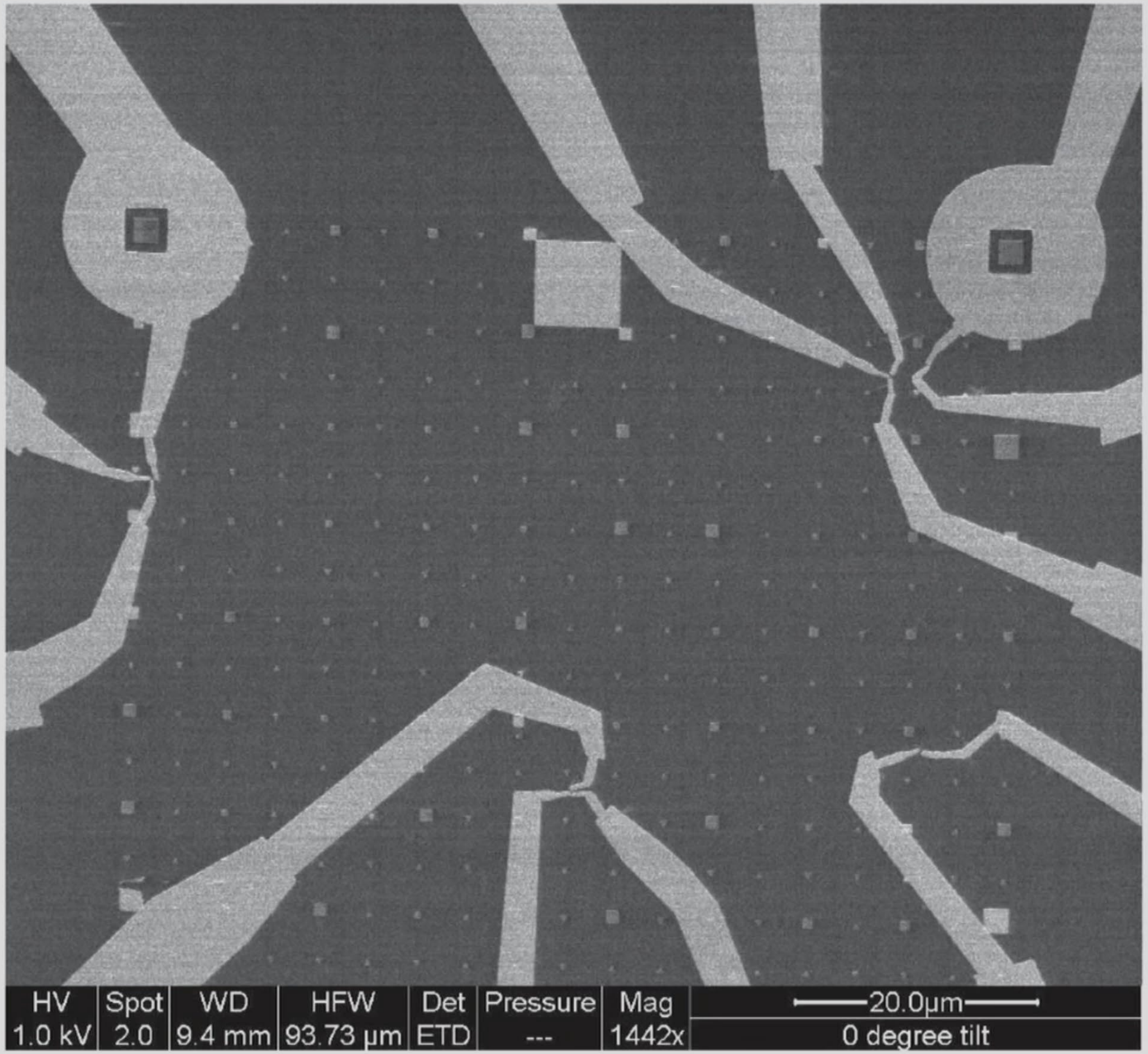


high

resolution

mapping

“Hunt and Peck Connect”



Tedious! **Miserable!** **Inefficient!** **Unscalable!**

Current approaches to integrating top-down and bottom-up components are not scalable

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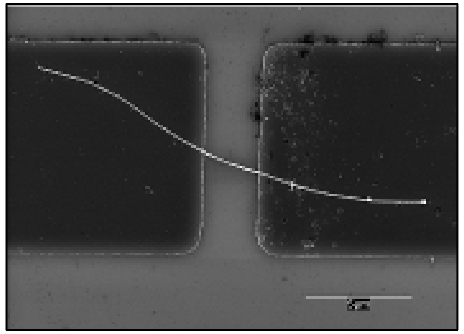

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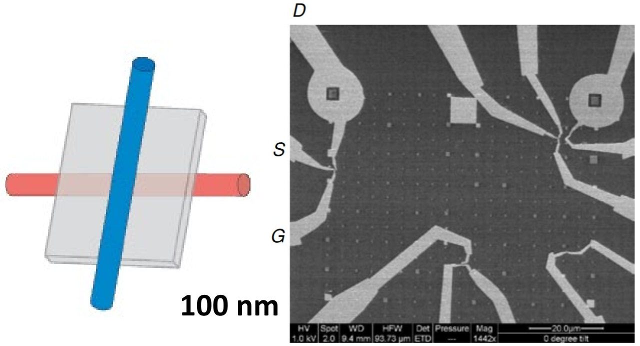

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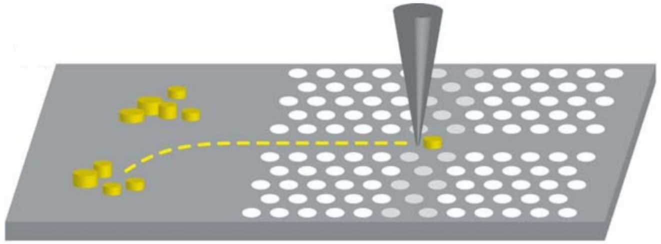
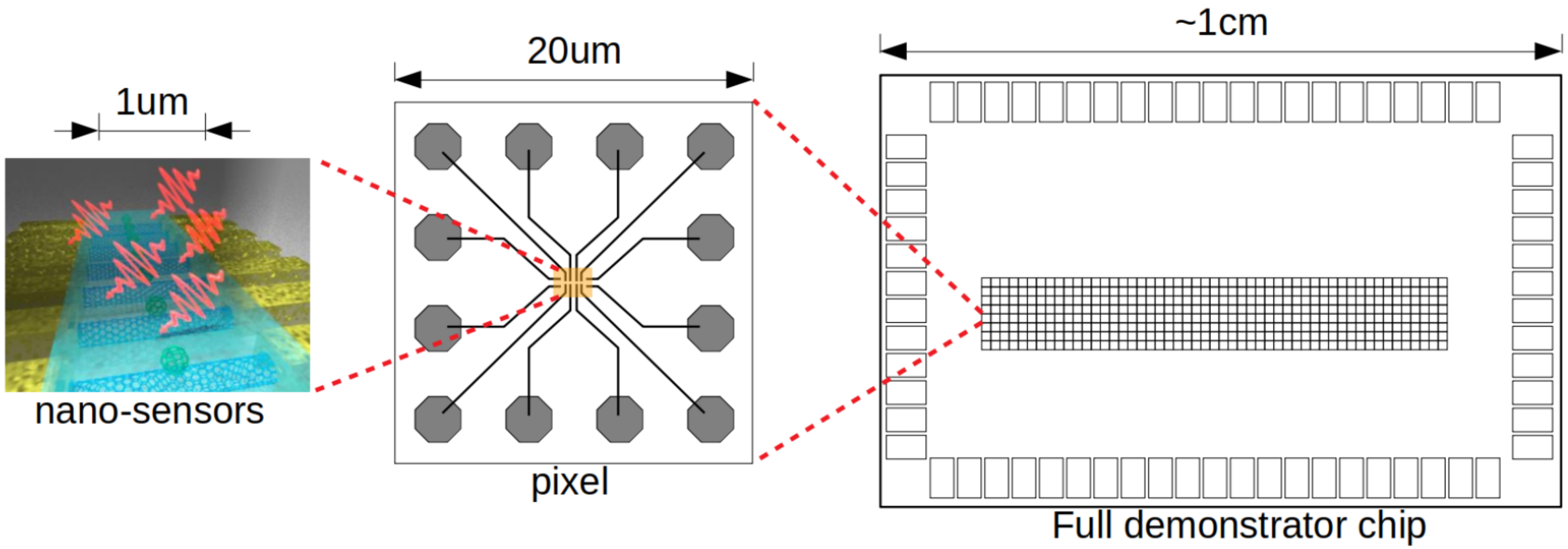


Barth et al, Optic Letters, 2009

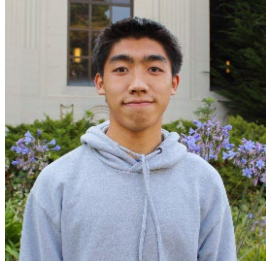
Single photon sensor with color resolution



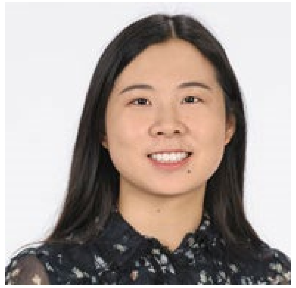
Nanometer-precise DSA with DNA

Yunjeong Park

Lin Du

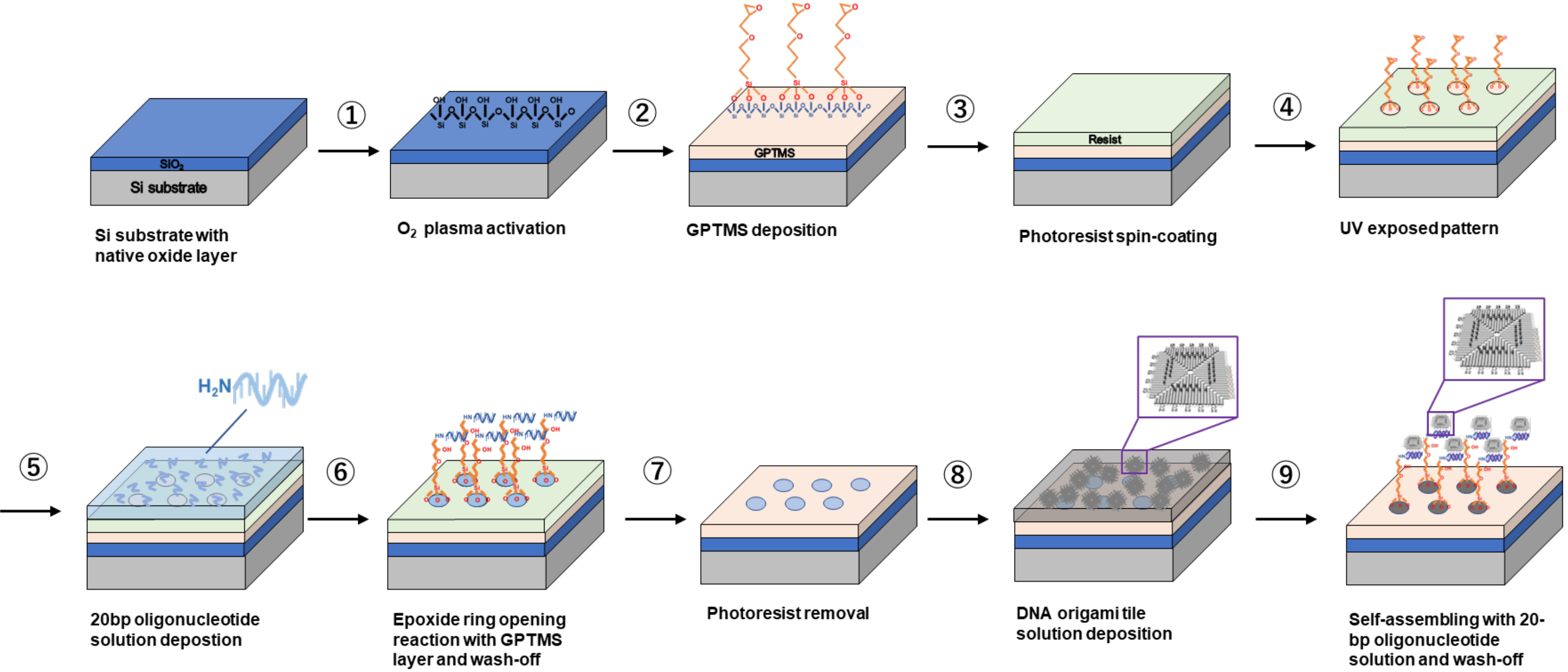


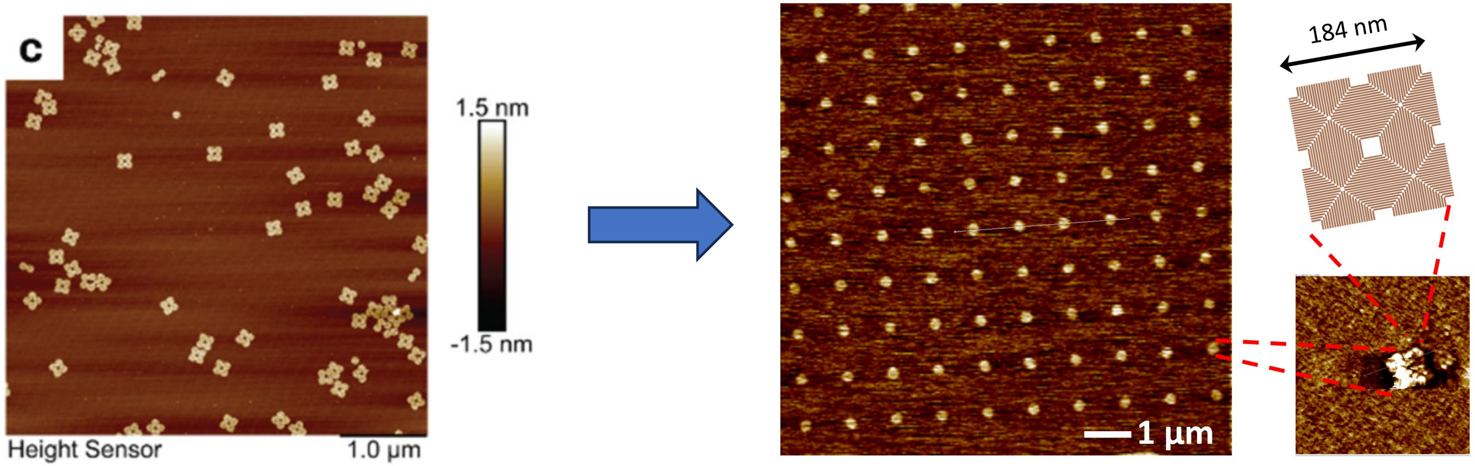
Leo Huang



Beihang Yu

Ricardo Ruiz





Single photon sensor with color resolution

1) CNTs are a pain (aggregation, polydispersity). Look for alternative 1D carriers (Te wires?).
2) Continue development of precision placement.

Ti Lab @ UC Berkeley

Lin Du, EE PhD in MEMS and microfabrication

Yifeng Shi, ChE PhD in nanoparticle synthesis

Benjamin Cary, EE MS in power electronics

Samson Petrosyan, BS in CS, Economics, Data Science

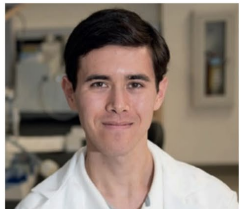
Myoungseok Kim, MS in DNA nanotechnology

Durham Smith, EE MS in robotics

Yunjeong Park PhD in Nanotechnology

Soyeon Lee PhD in Material Science

Jared Huzar Biophysics



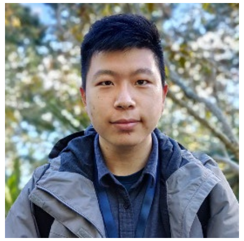
Phil Petersen PhD in DNA nanotechnology, MD residency in pathology

Lexi Webster, BS Physics

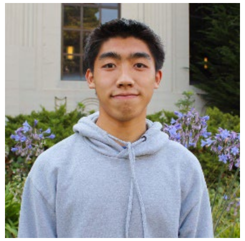
Astha Nimavat Molecular Biology

Erina Iwasa, BS Engineering

Arjun Banerjee Eng undergrad



Jack Wang Molecular Biology



Leo Huang EECS

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National Institutes of Health