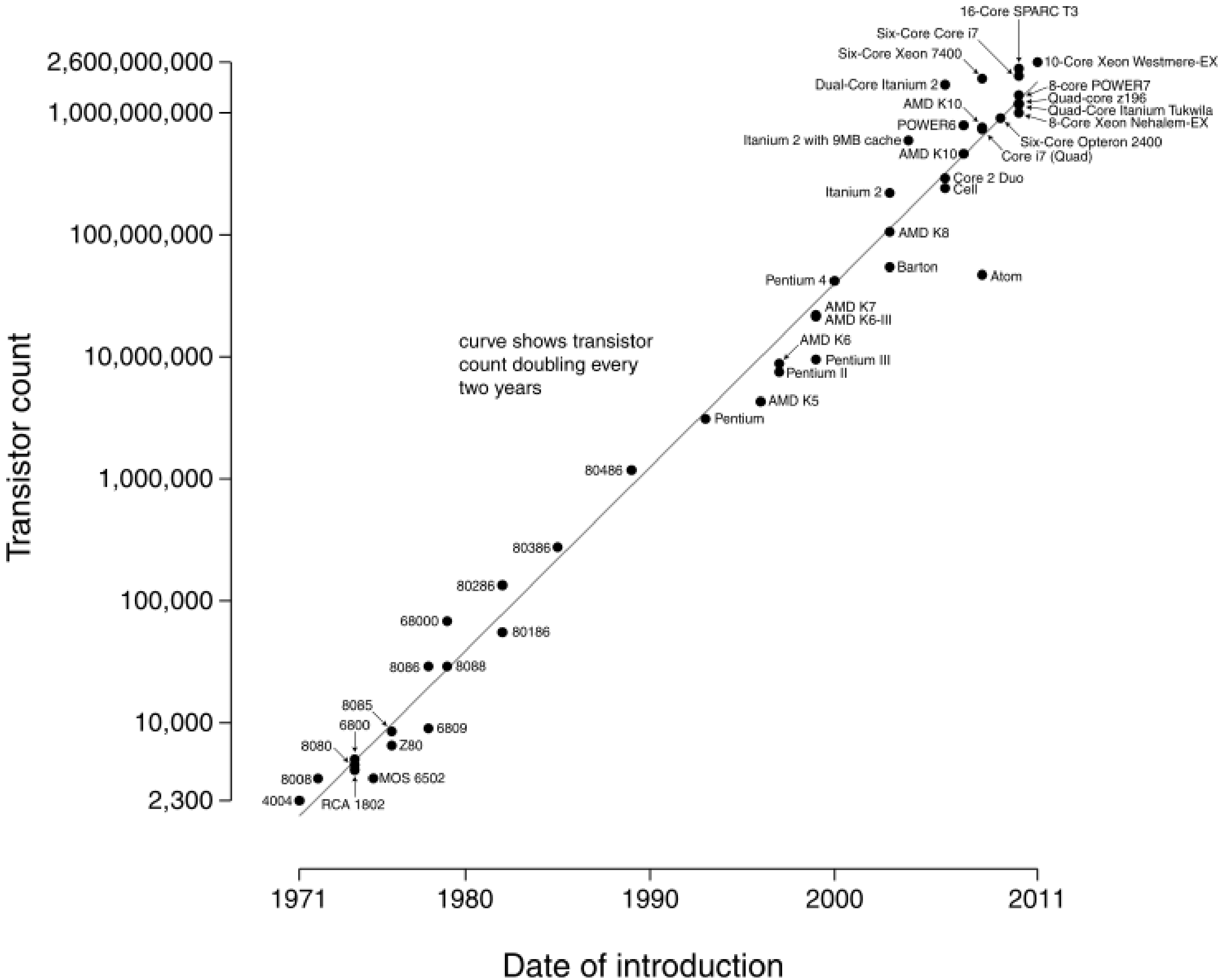
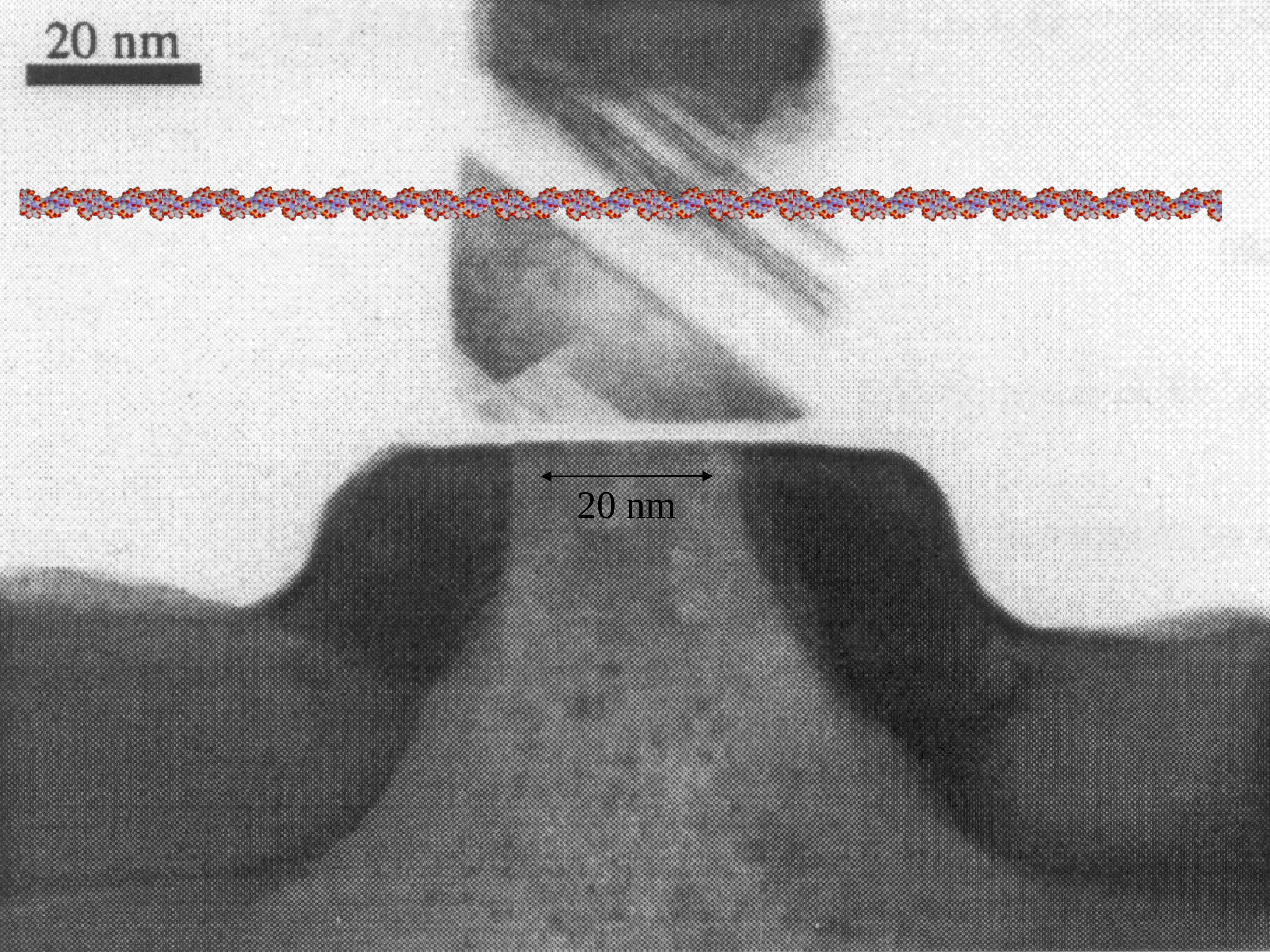
Microprocessor Transistor Counts 1971-2011 & Moore's Law



http://en.wikipedia.org/wiki/Moore%27s_law#mediaviewer/File:Transistor_Count_and_Moore%27s_Law_-_2011.svg



20 nm
20 nm

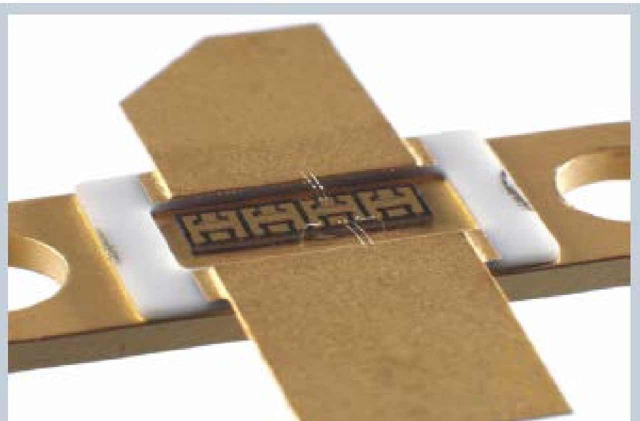
International Technology Roadmap for Semiconductors

Table PIDS2a High-performance (HP) Logic Technology Requirements - TCAD																
Year of Production	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*	*2023*	*2024*	*2025*	*2026*	*2027*	*2028*
Logic Industry "Node Range" Labeling (nm) [based on 0.71x reduction per "Node Range" ("Node" = "2x Mx)	"16/14"		"11/10"		"8/7"		"6/5"		"4/3"		"3/2.5"		"2/1.5"		"1/0.75"	
MPU/ASIC Metal 1 (M1) ½ Pitch (nm) (contacted)	40	32	32	28.3	25.3	22.5	20.0	17.9	15.9	14.2	12.6	11.3	10.0	8.9	8	7.1
L_g : Physical Gate Length for HP Logic (nm)	20	18	16.7	15.2	13.9	12.7	11.6	10.6	9.7	8.8	8.0	7.3	6.7	6.1	5.6	5.1
L_{ch} : Effective Channel Length (nm) [3]	16.0	14.4	13.4	12.2	11.1	10.2	9.3	8.5	7.8	7.0	6.4	5.8	5.4	4.9	4.5	4.1
V_{dd} : Power Supply Voltage (V)																
Bulk/SOI/MG	0.86	0.85	0.83	0.81	0.80	0.78	0.77	0.75	0.74	0.72	0.71	0.69	0.68	0.66	0.65	0.64
EOT: Equivalent Oxide Thickness																
Bulk/SOI/MG (nm)	0.80	0.77	0.73	0.70	0.67	0.64	0.61	0.59	0.56	0.54	0.51	0.49	0.47	0.45	0.43	0.41
Dielectric constant (K) of gate dielectrics	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0	18.5	19.0	19.5	20.0
Physical gate oxide thickness (nm)	2.56	2.57	2.53	2.51	2.49	2.46	2.42	2.42	2.37	2.35	2.29	2.26	2.23	2.19	2.15	2.10
Channel Doping (10^{18} /cm^3) [4]																
Bulk	6.0	7.0	7.7	8.4	9.0											
SOI/MG	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Body Thickness (nm) [5]																
SOI																
MG	6.4	5.8	5.3	4.9	4.4	4.1	3.7	3.4	3.1	2.8	2.6	2.3	2.1	2.0	1.8	1.6
T_{BOX} : Buried Oxide Thickness for SOI (nm) [6]																
SOI																
CET: Capacitance Equivalent Thickness (nm) [7]																
Bulk/SOI/MG	1.10	1.07	1.03	1.00	0.97	0.94	0.91	0.89	0.86	0.84	0.81	0.79	0.77	0.75	0.73	0.71
C_{ch} intrinsic (fF/µm) [8]																
Bulk/SOI/MG	0.502	0.465	0.448	0.420	0.396	0.373	0.352	0.329	0.311	0.289	0.273	0.255	0.240	0.225	0.212	0.198
Mobility (cm^2 /V-s)																
Bulk	400	400	400	400	400											
SOI																
MG	250	250	250	250	250	250	200	200	200	200	200	150	150	150	150	150
I_{off} (nA/µm) [9]																
Bulk/SOI/MG	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
$I_{d,sat}$: NMOS Drive Current (µA/µm) [10]																
Bulk	1,348	1,355	1,340	1,295	1,267											
SOI																
MG	1670	1,680	1,700	1,660	1,660	1,610	1,600	1,480	1,450	1,350	1,330	1,170	1,100	1,030	970	900
$V_{t,lin}$ (V) [11]																
Bulk	0.306	0.327	0.334	0.357	0.378											
SOI																
MG	0.219	0.225	0.231	0.239	0.264	0.266	0.265	0.276	0.295	0.303	0.306	0.319	0.334	0.340	0.354	0.364

http://www.itrs.net/reports.html

CMORE - heterogeneous integration

For pMOS a strained Ge channel and for nMOS a strained InGaAs channel (with high In content) promises to be the best way for further CMOS scaling.

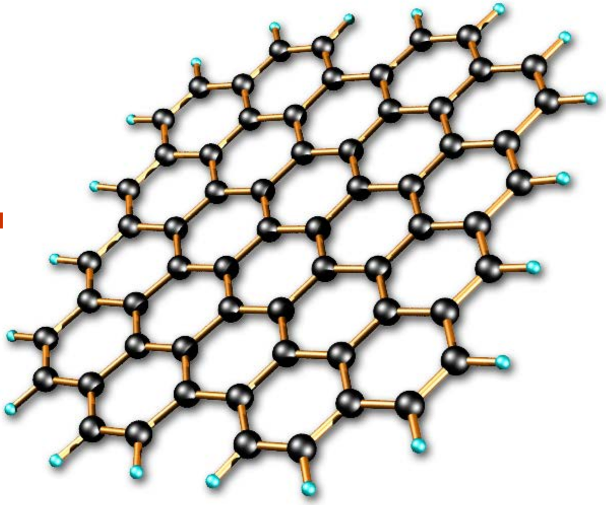


System-in-a-package assembly of AlGaN/GaN HEMT power bar using a dedicated power package with direct heat sink.

GaN-on-silicon technology

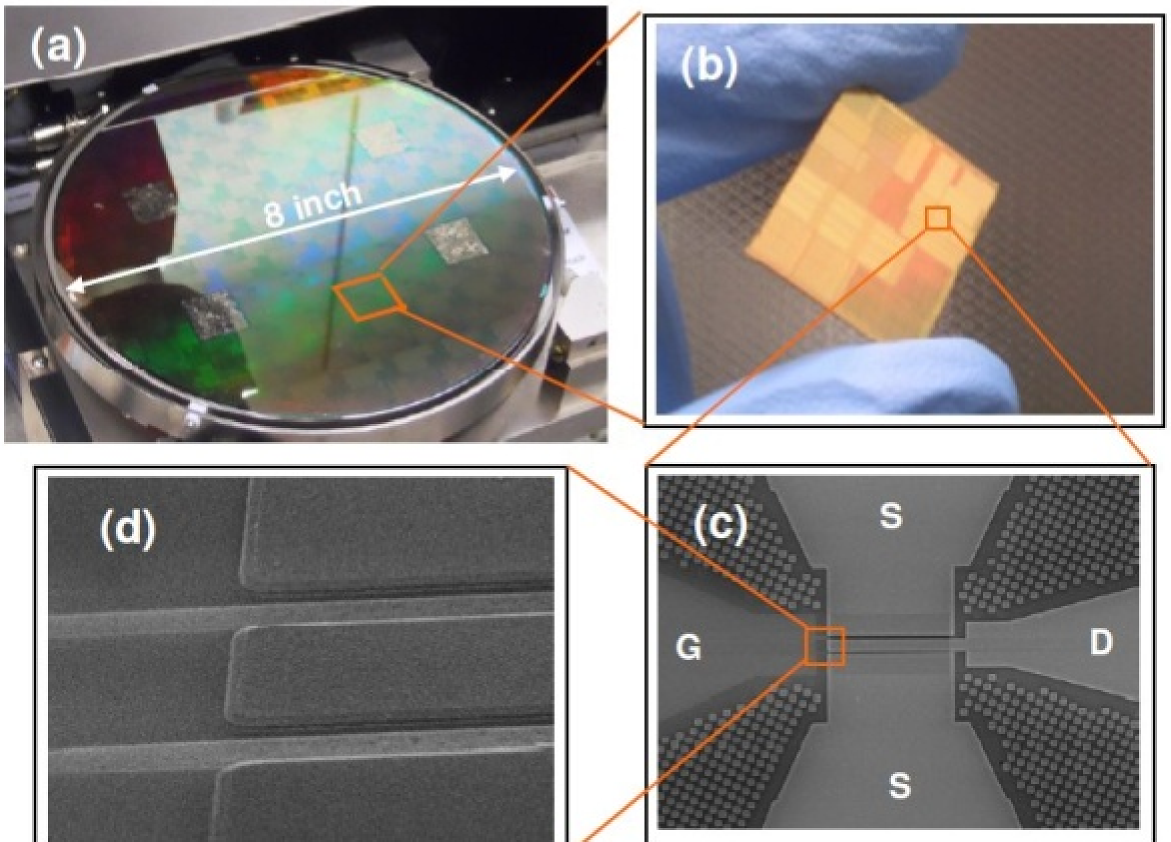
http://www.imec-nl.nl/nl_en/research/cmore---heterogeneous-integratio.html

Graphene



- Graphene transistors (on a Si substrate)

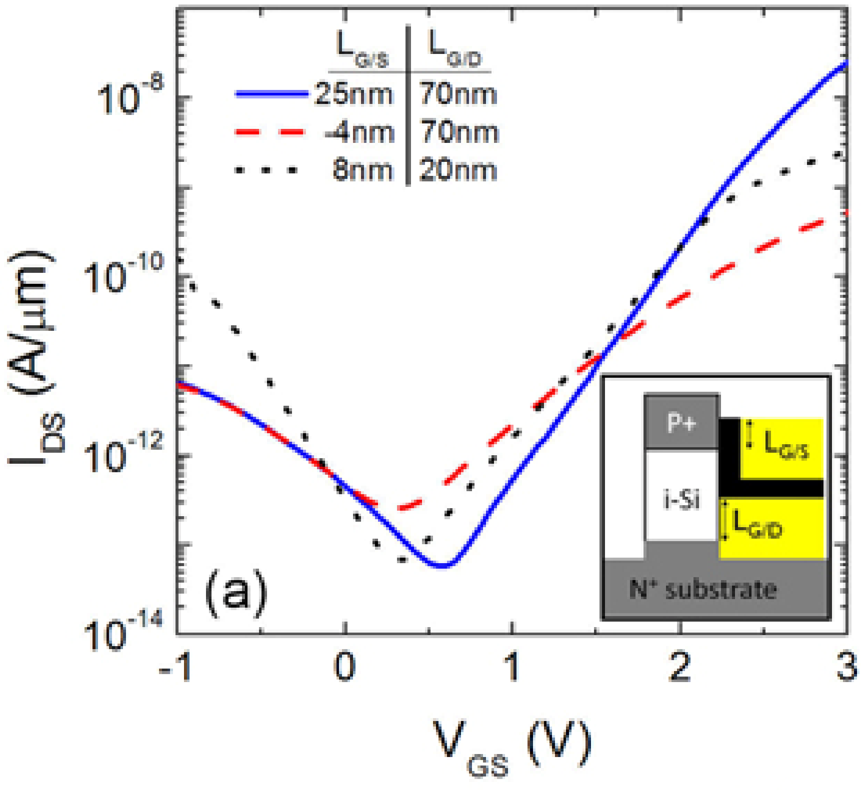
Gate length 1 micron



http://www.zdnet.com/ibm-spins-nanotubes-wire-and-graphene-3040094603/

Tunnel FETs

One of the most promising candidates is the tunnel field-effect transistor (FET), which is a gated-diode operating based on band-to-band tunneling at the junction. The gate voltage changes the distance the electrons need to tunnel.



http://www.imec.be/ScientificReport/SR2011/1414174.html

Miniaturization ends with CMOS

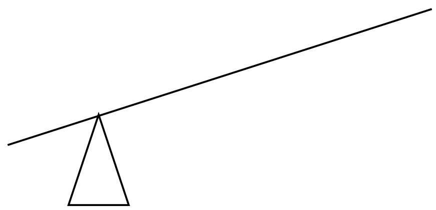
There are no technologies (single electron transistors, molecular electronics, superconducting electronics, spintronics, NEMs...) that can provide performance similar to CMOS at a **much** smaller size scale.

There are presently no transistors cheaper than silicon transistors

Candidates for orders of magnitude improvements of performance are quantum computing and molecular electronics.

Gain requires leverage

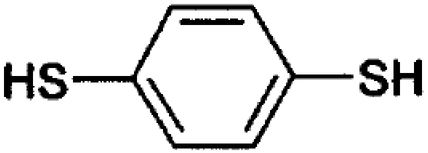
There are two lengths in an amplifier.

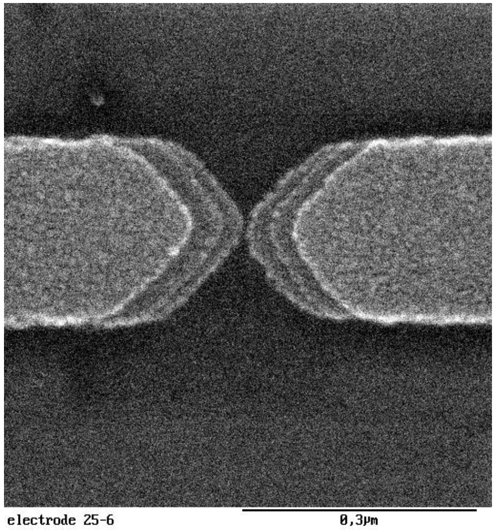


In CMOS the gate insulator is much thinner than the gate length.

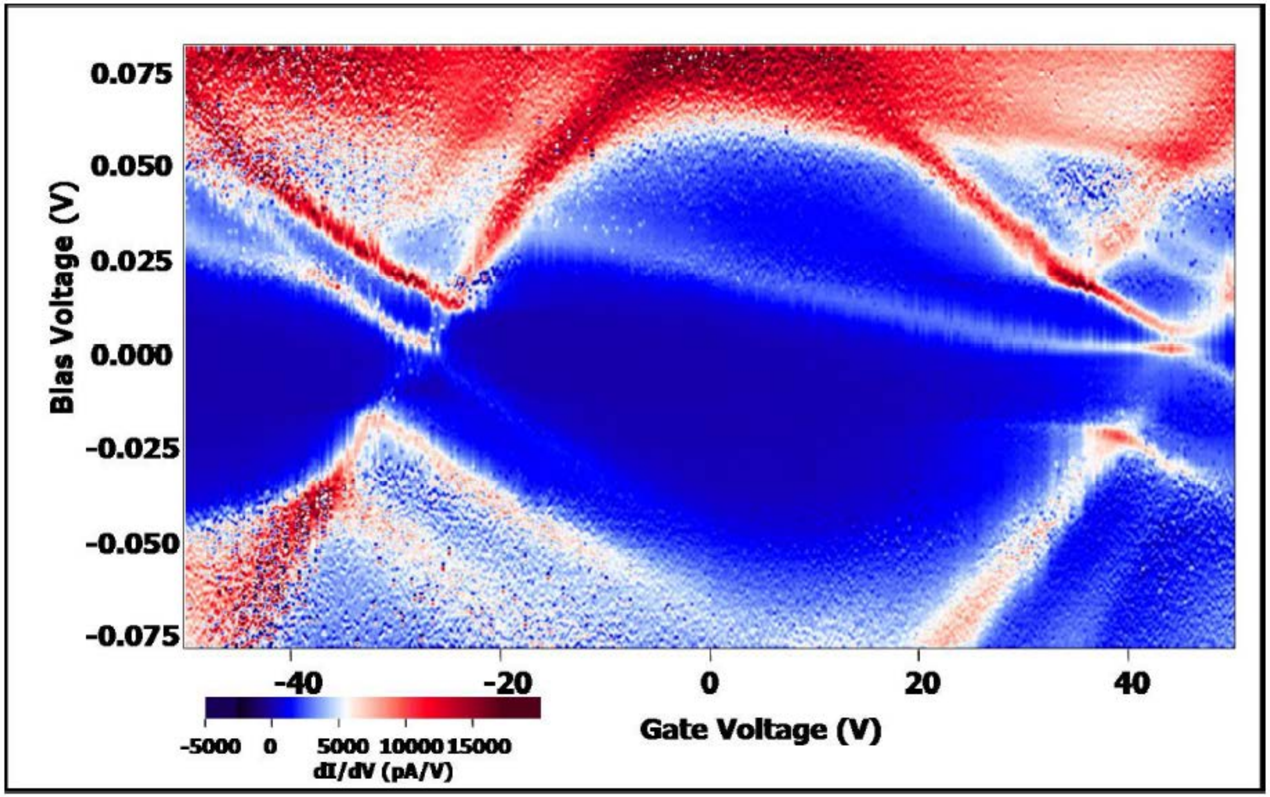
If the short length is 1 nm, the long length is 10 nm.

Measuring molecules



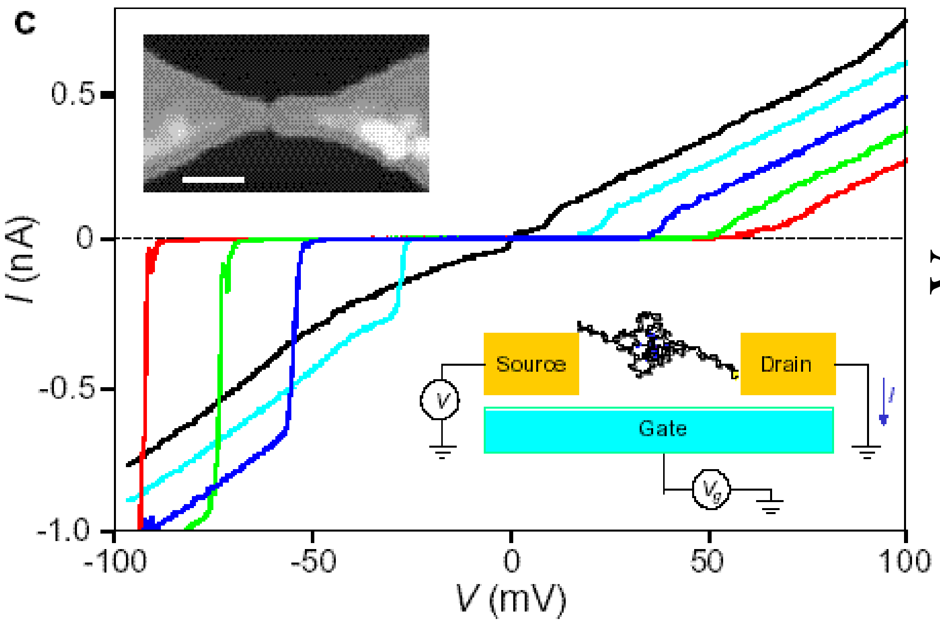


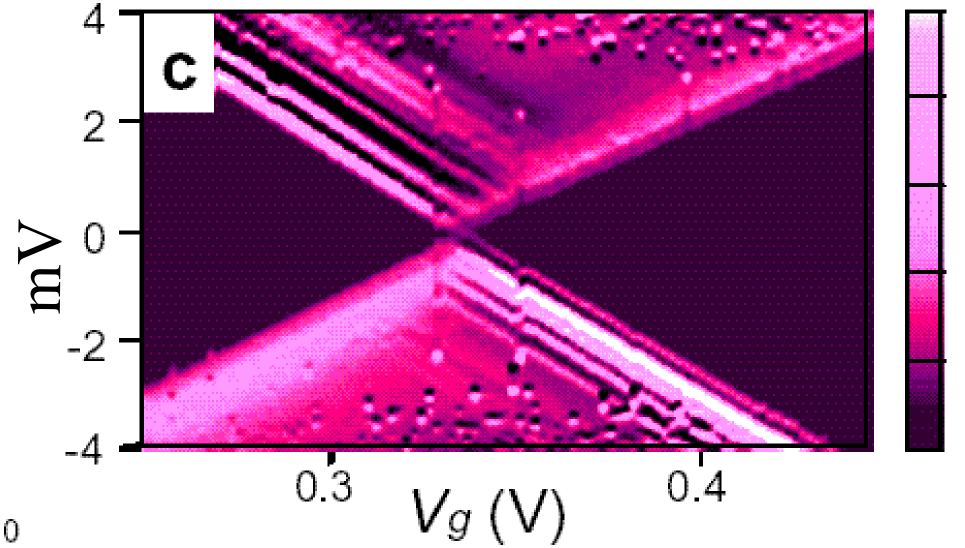
1,4-benzenedithiol



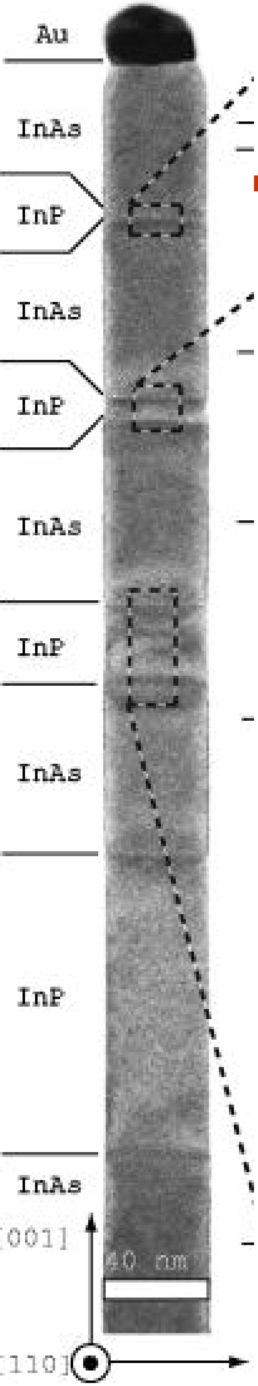
Results are unreproducible

Molecular electronics





Jiwoong Park, Abhay N. Pasupathy, Jonas I. Goldsmith, Connie Chang, Yuval Yaish, Jason R. Petta, Marie Rinkoski, James P. Sethna, Héctor D. Abruña, Paul L. McEuen, and Daniel C. Ralph, Nature 417 p. 722 (2002).

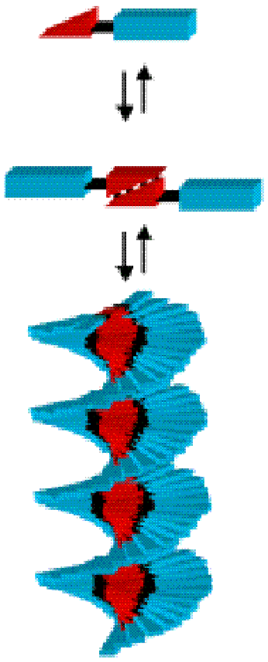


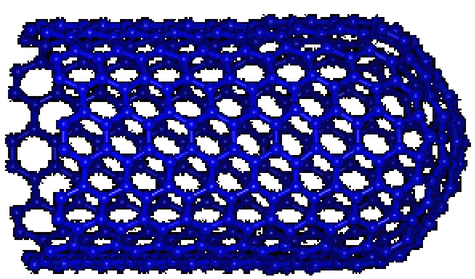
Use big 'molecules' as electronic components

Easier to make reproducible contacts.

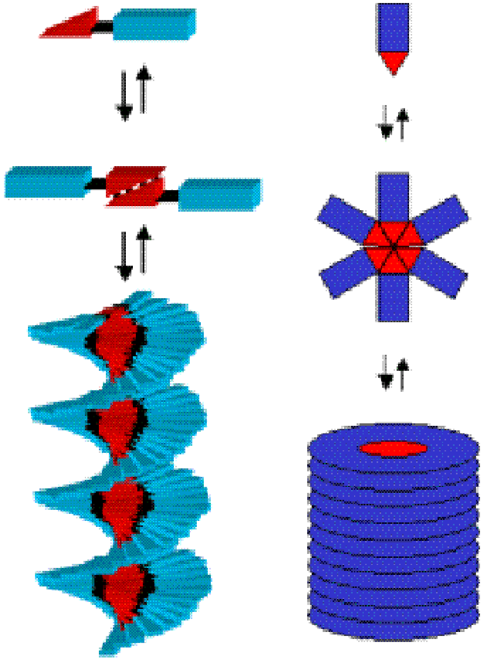
Imaging of individual molecular assemblies possible

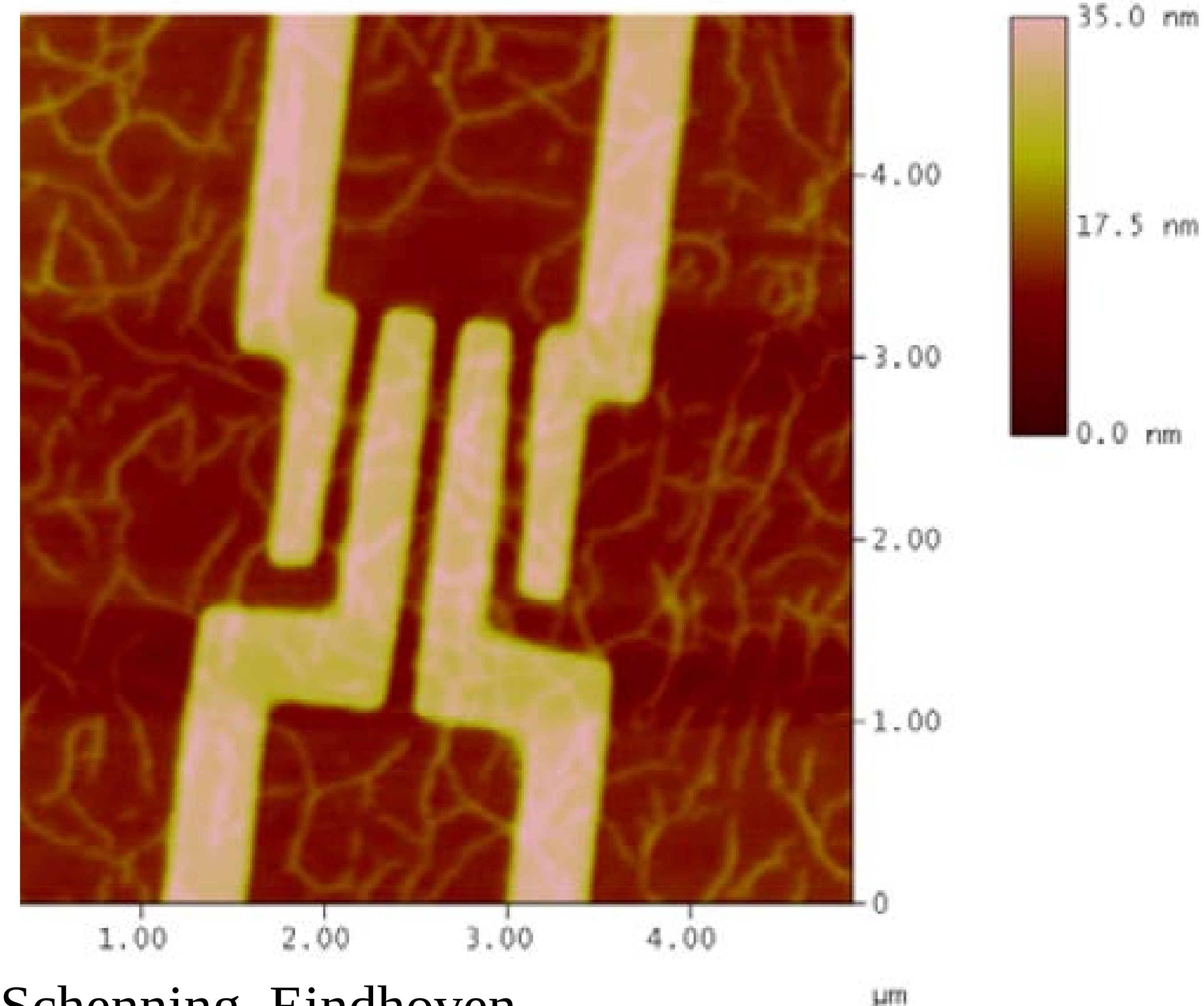
Nanowires or nanocrystals of conventional semiconductors





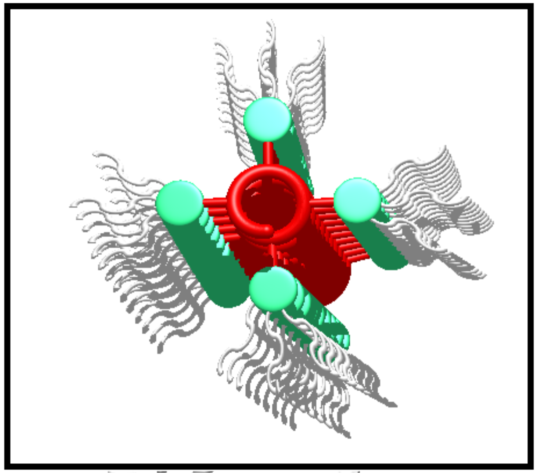
AFM image of MOPV4 fibers

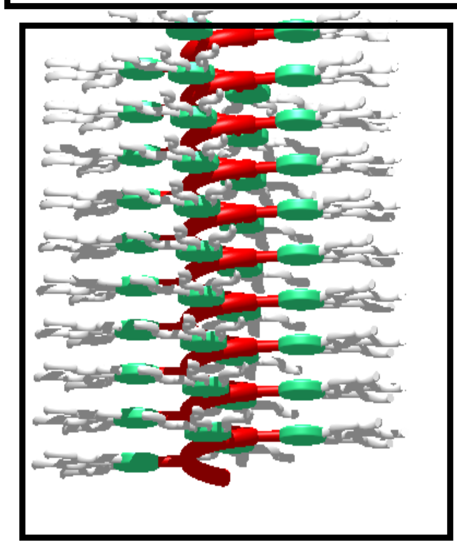


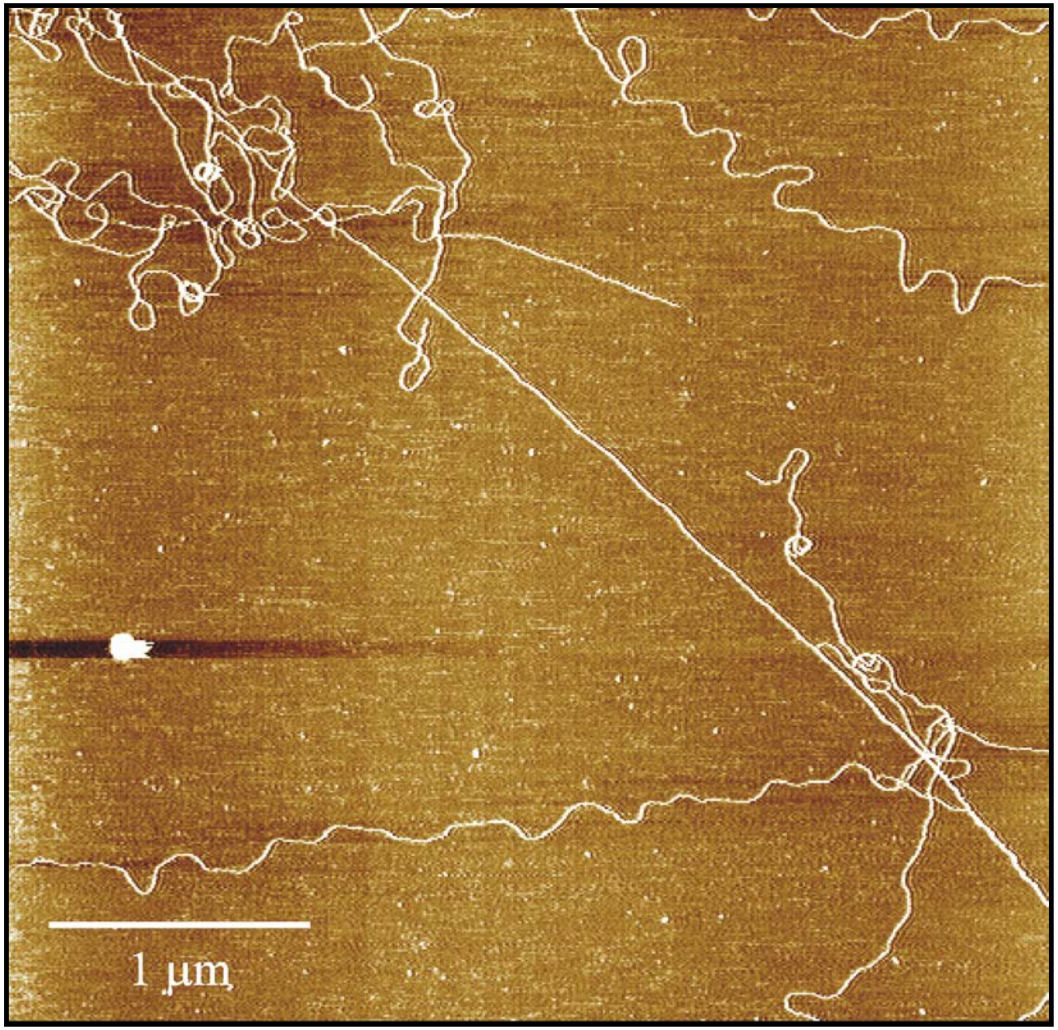


Albert Schenning, Eindhoven

Using templates for self-assembly



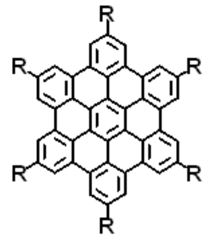




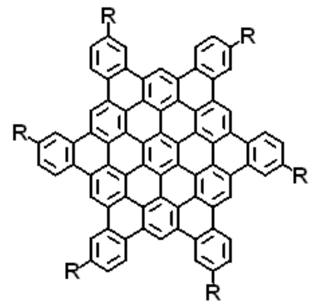
Alan Rowan, Nijmegen

Phthalocyanine Polyisocyanides

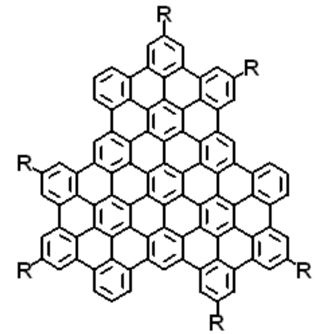
hexabenzocoronenes



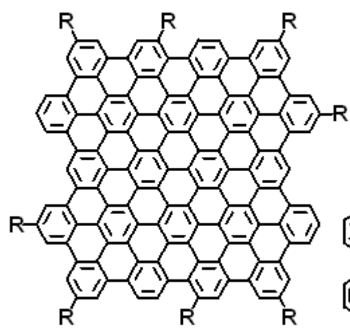
C42 (HBC)



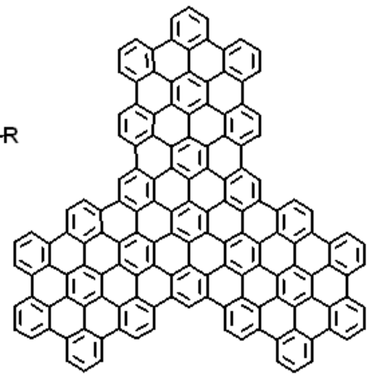
C78



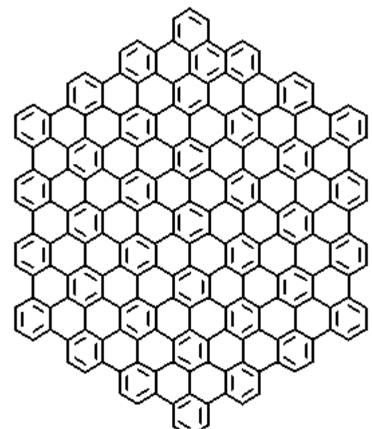
C96



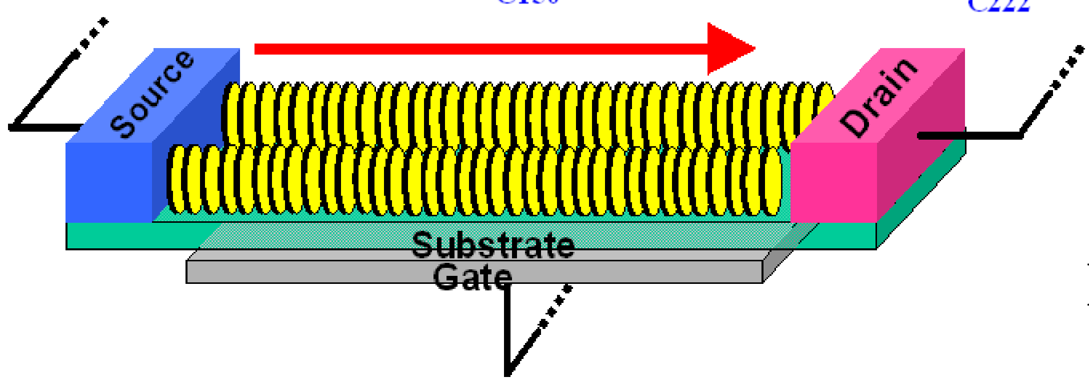
C132



C150

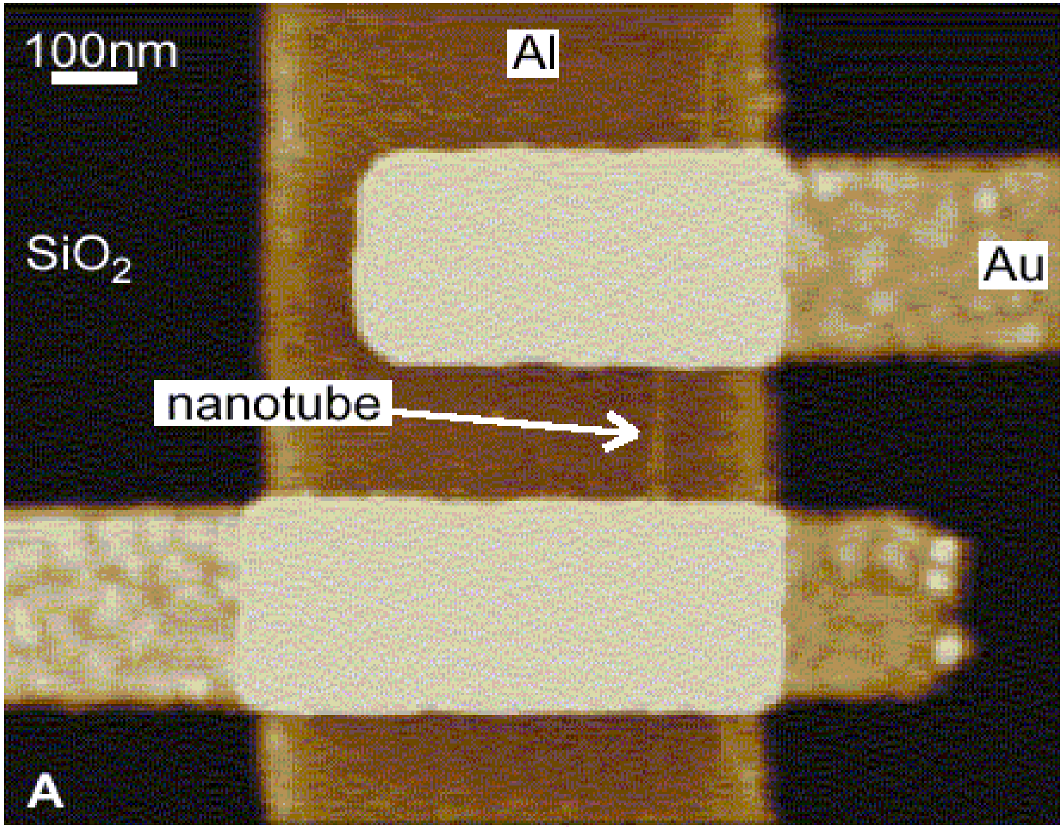


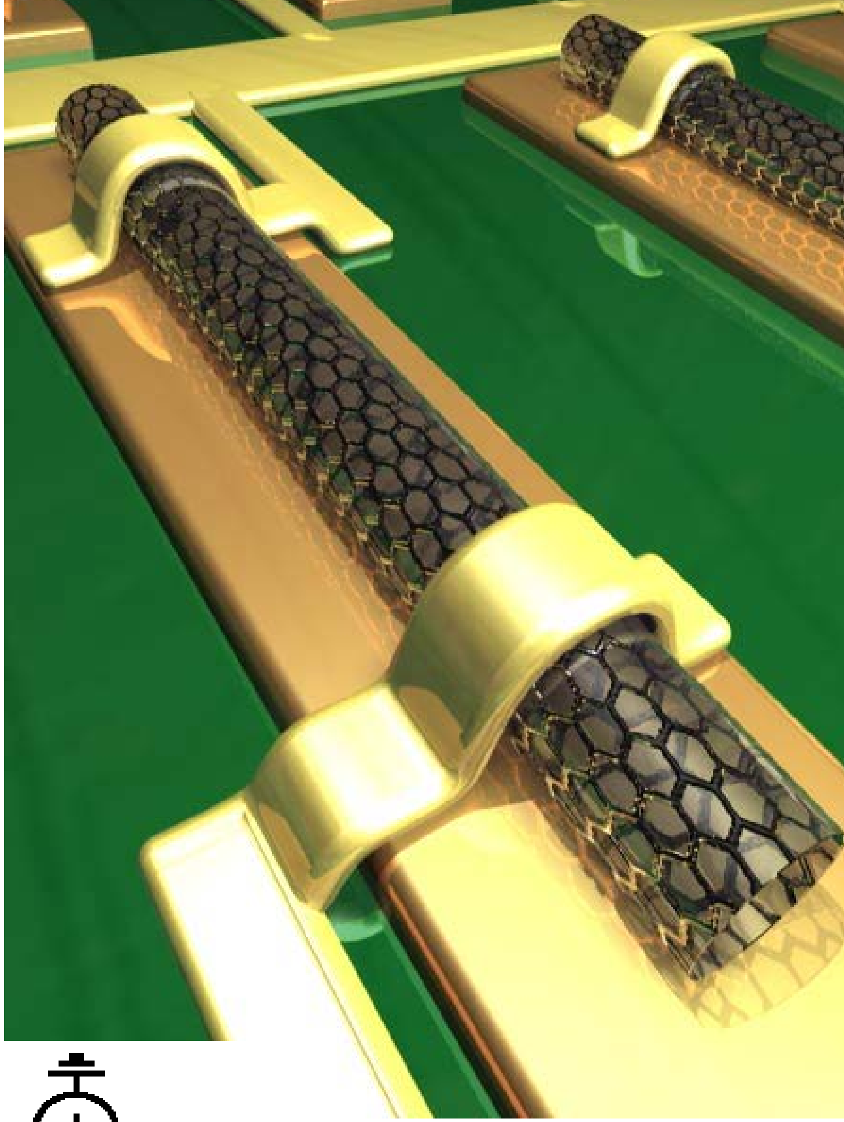
C222

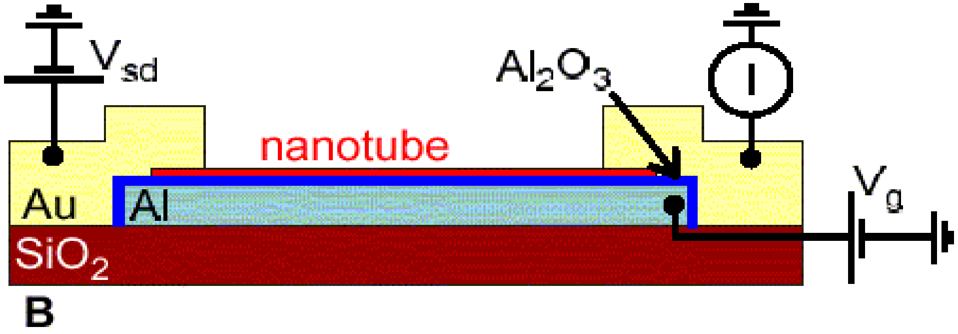


Müllen, Mainz

Carbon nanotube transistors







After Miniaturization

Increasing the level of self-assembly in a fabrication process will replace miniaturization as a guiding principle for making cheaper circuits.

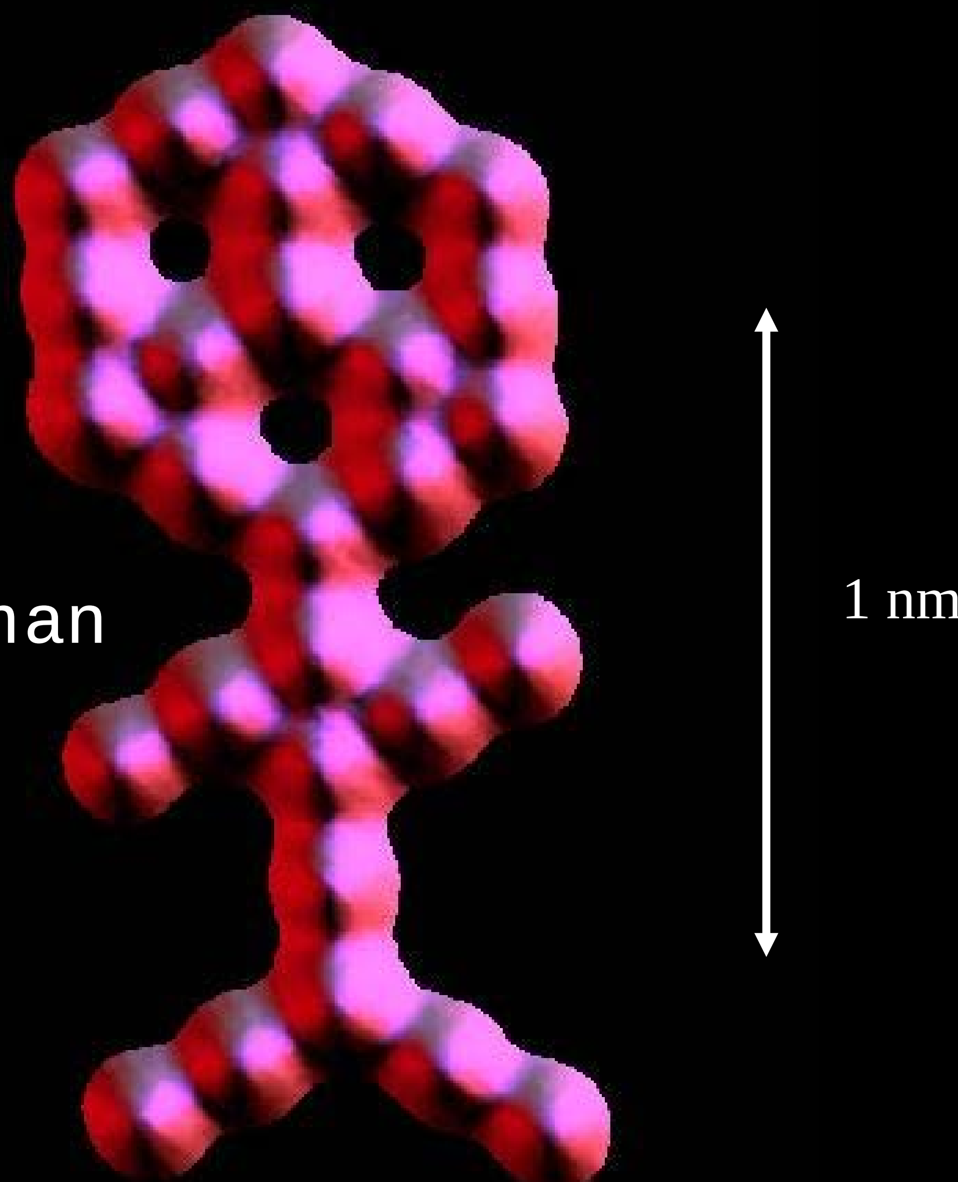
Molecular transistors must be large molecules. Transistors will have dimensions of ~10 nm

Low current drive of molecular devices will mean they will have to be put in parallel.

Lighting panels and solar cells will be the first self-assembled devices.

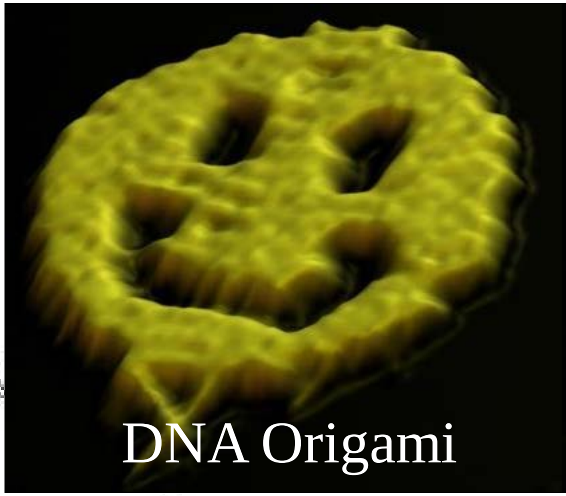
Organic microprocessor

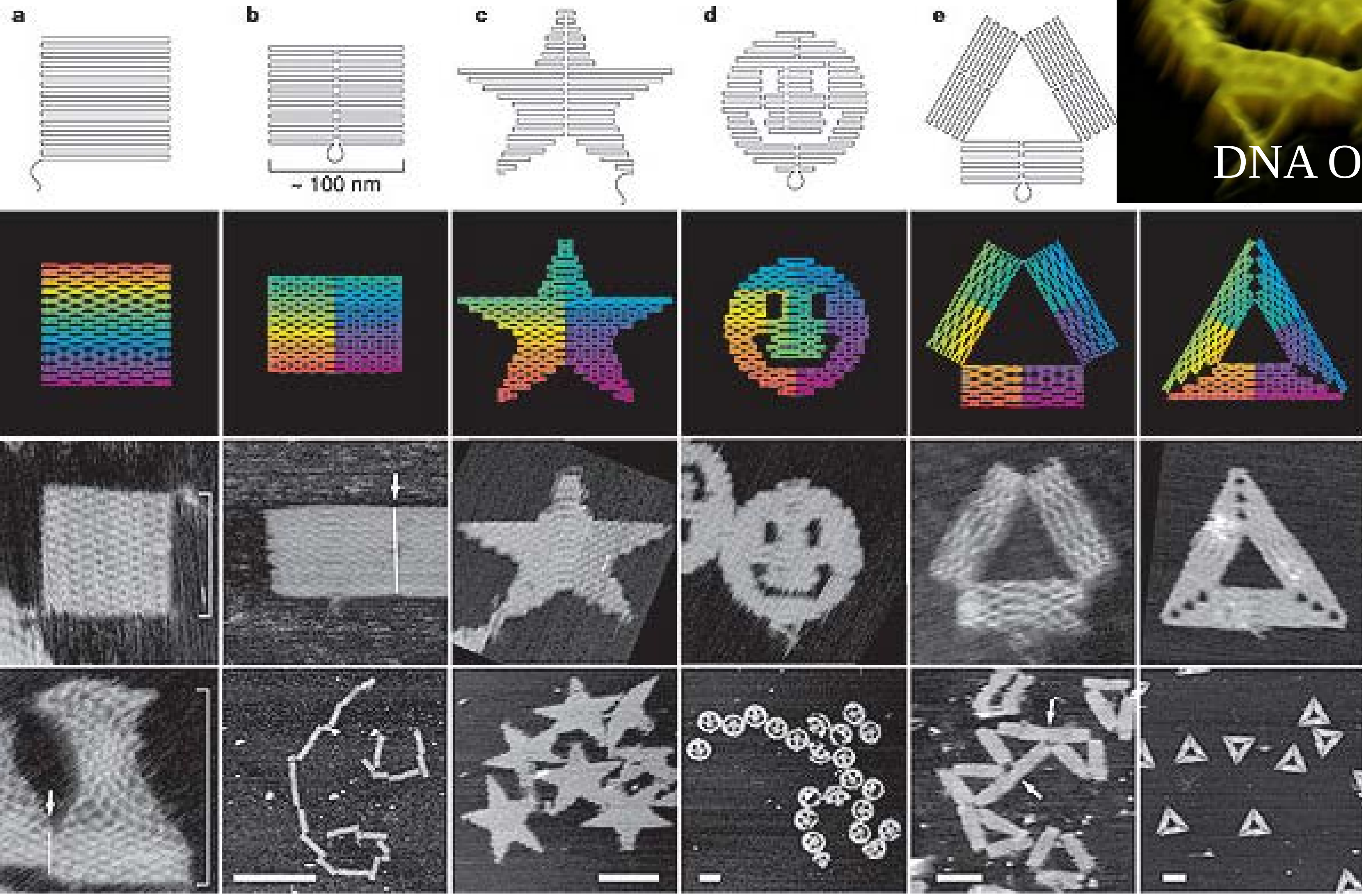
A modern computer has the processing power of a mosquito brain.



Carbon monoxide man

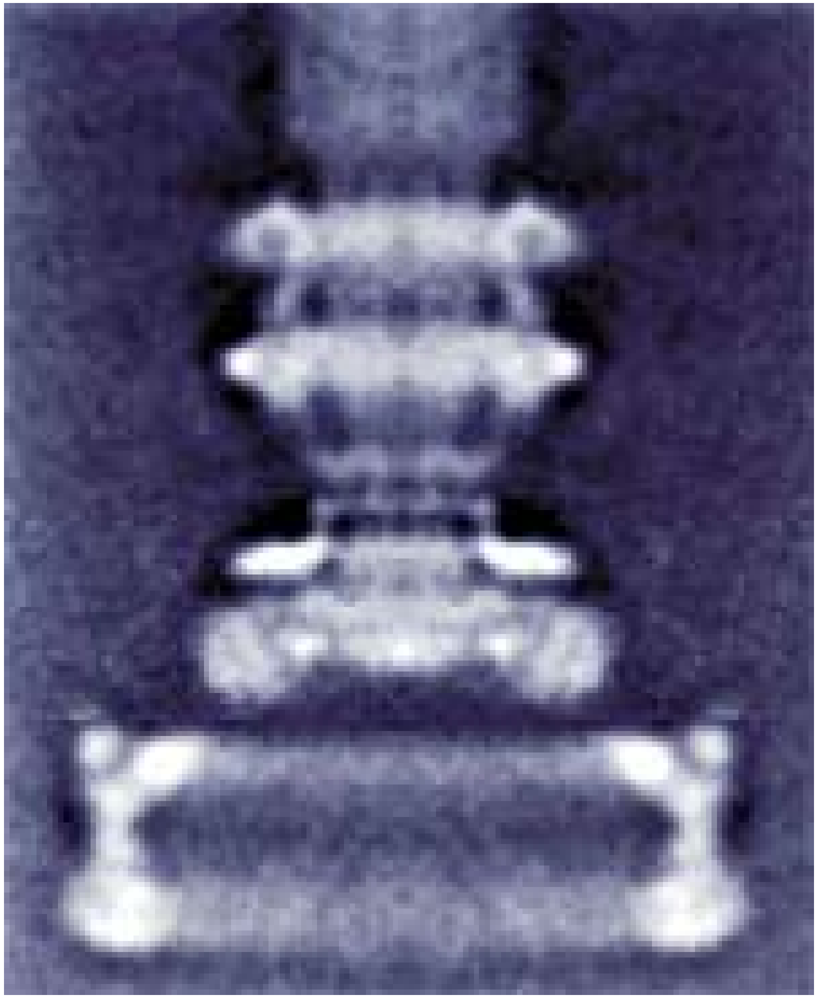
Bottom-up technology

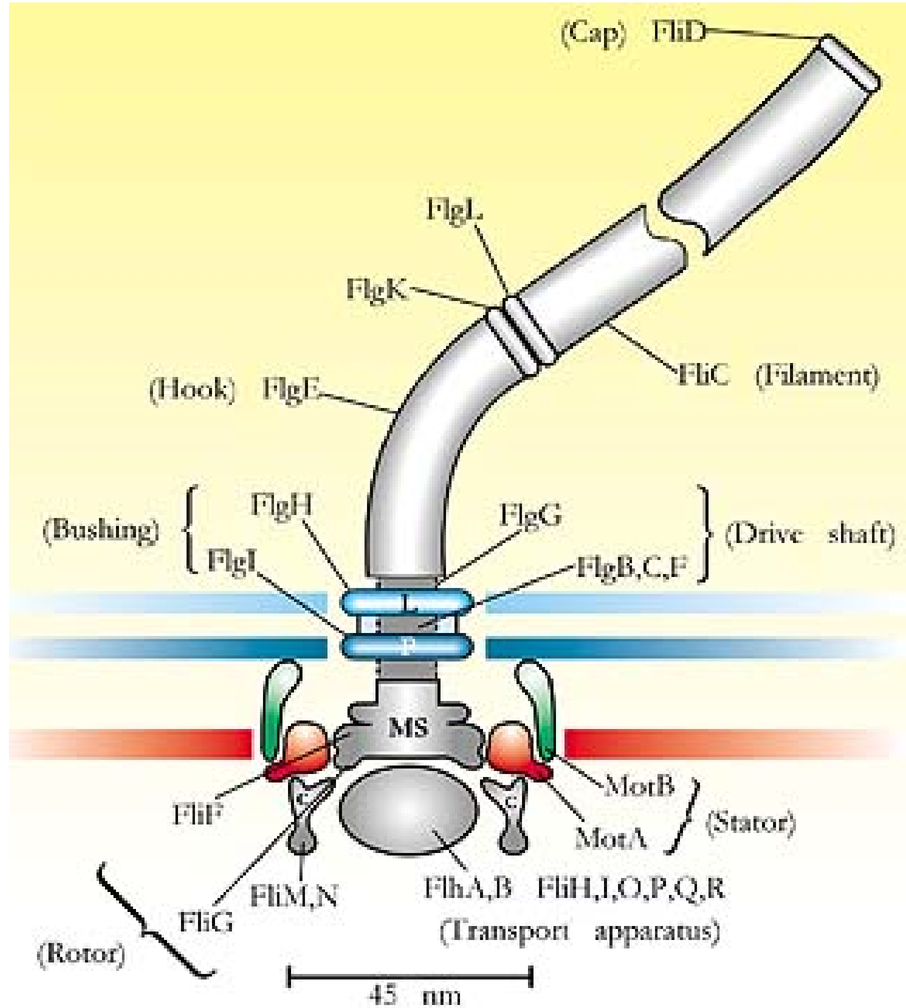




(Images: Paul Rothemund)

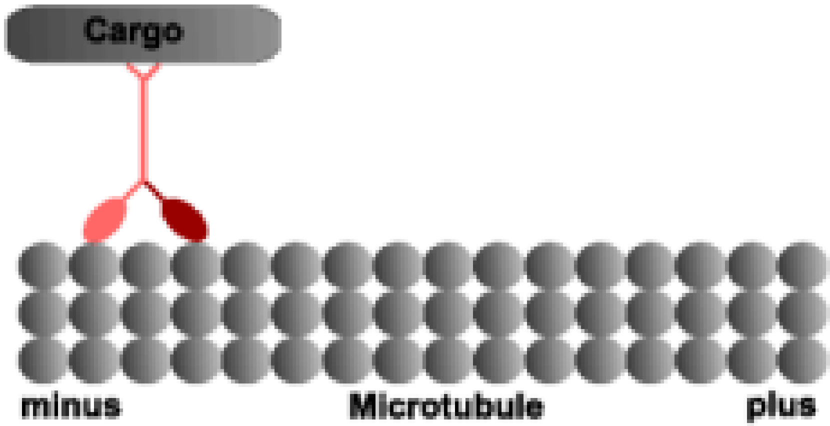
Bottom-up technology



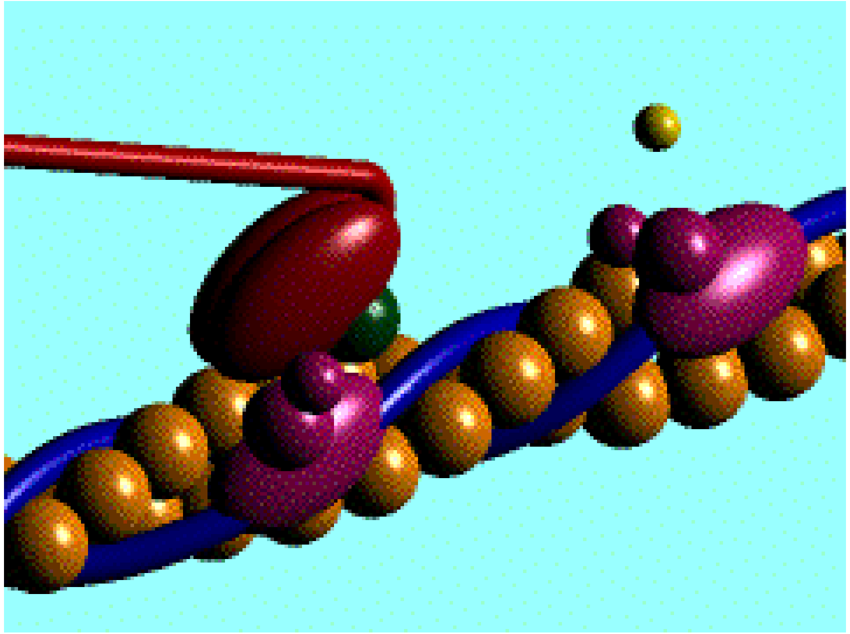


Bacterial motor

Bottom-up technology



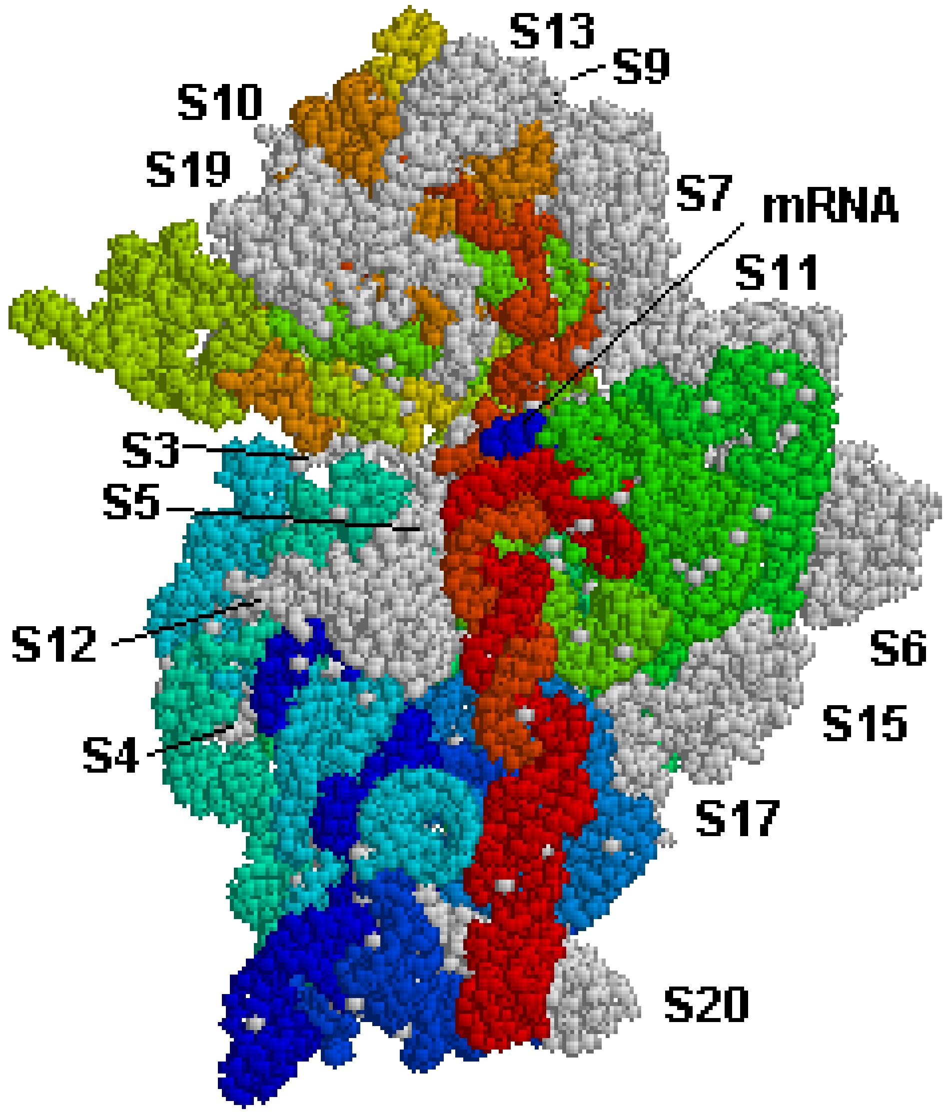
Kinesin



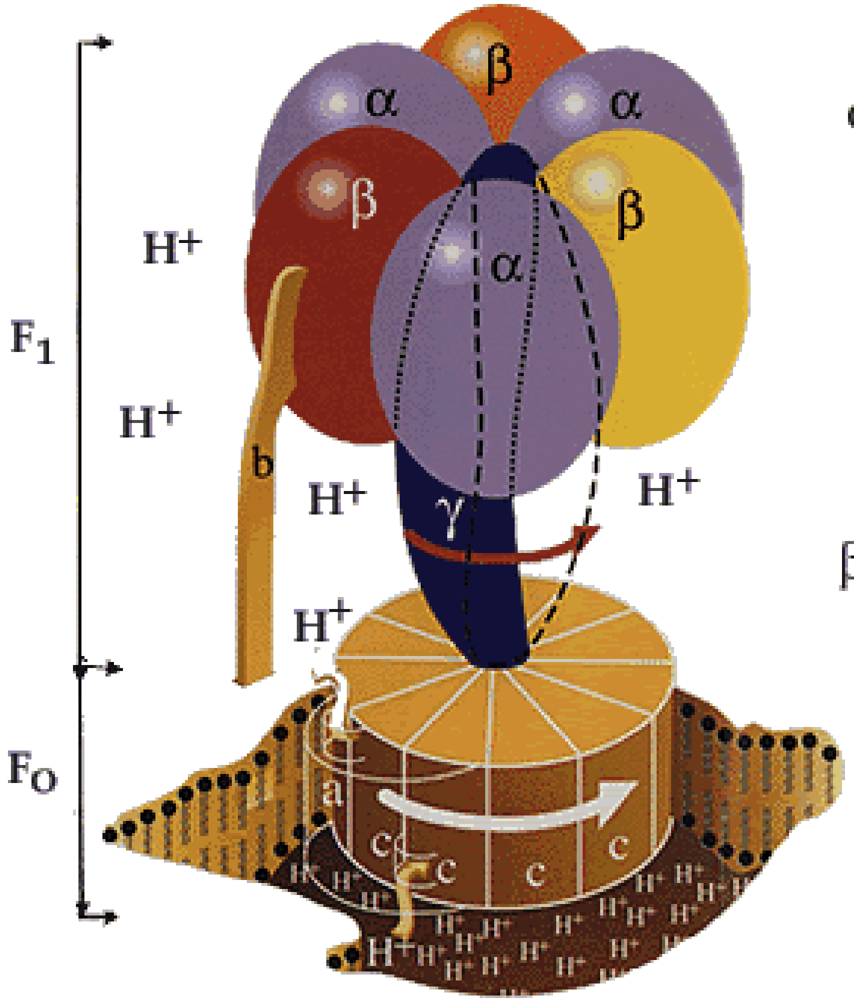
myosin-actin

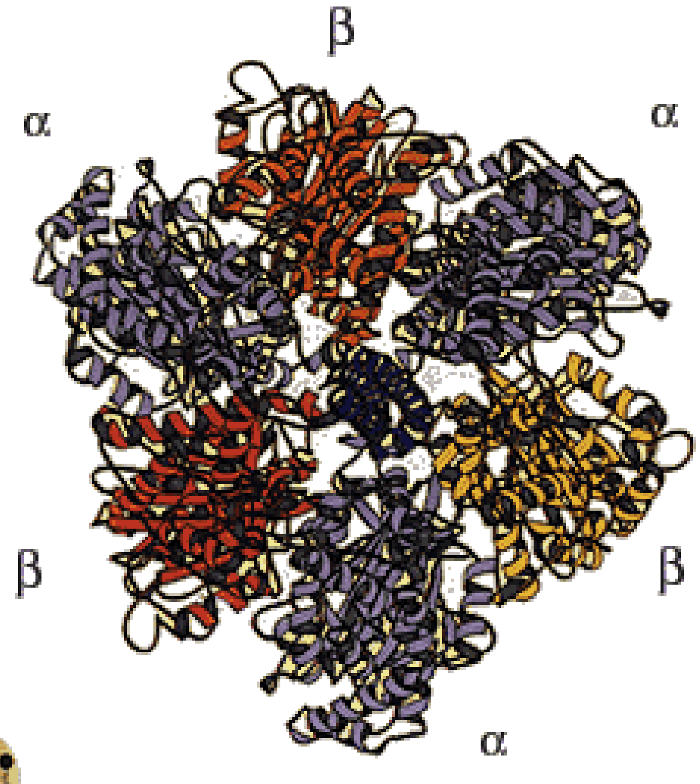
Ribosome

Ribosome



Nanomachines

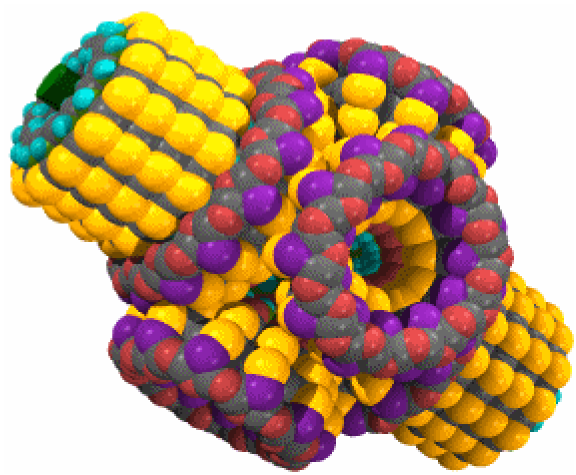


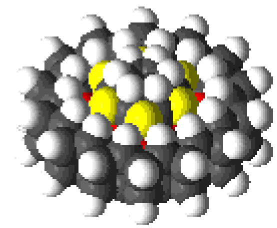


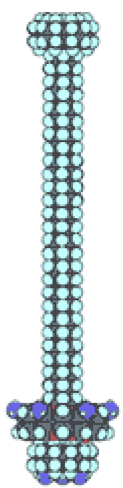
F_1 viewed from below

ATP-ase

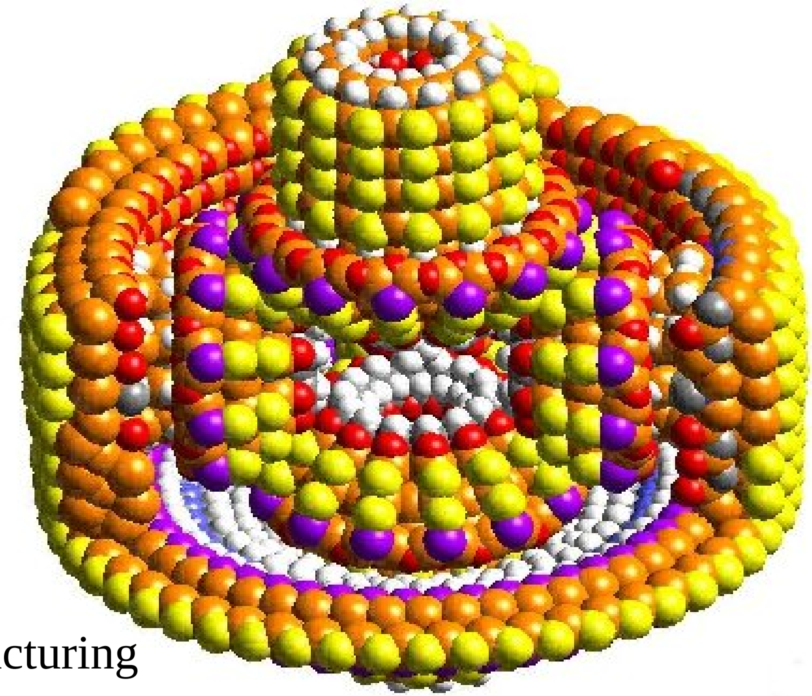
Atomistic Design





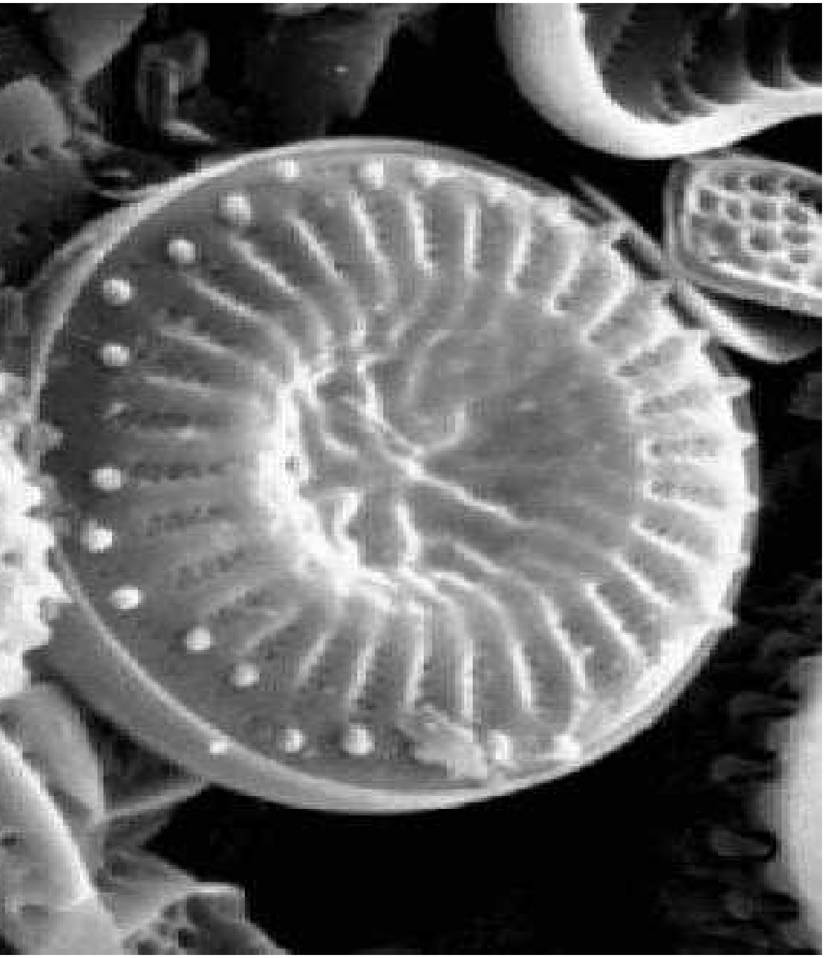


0 ps

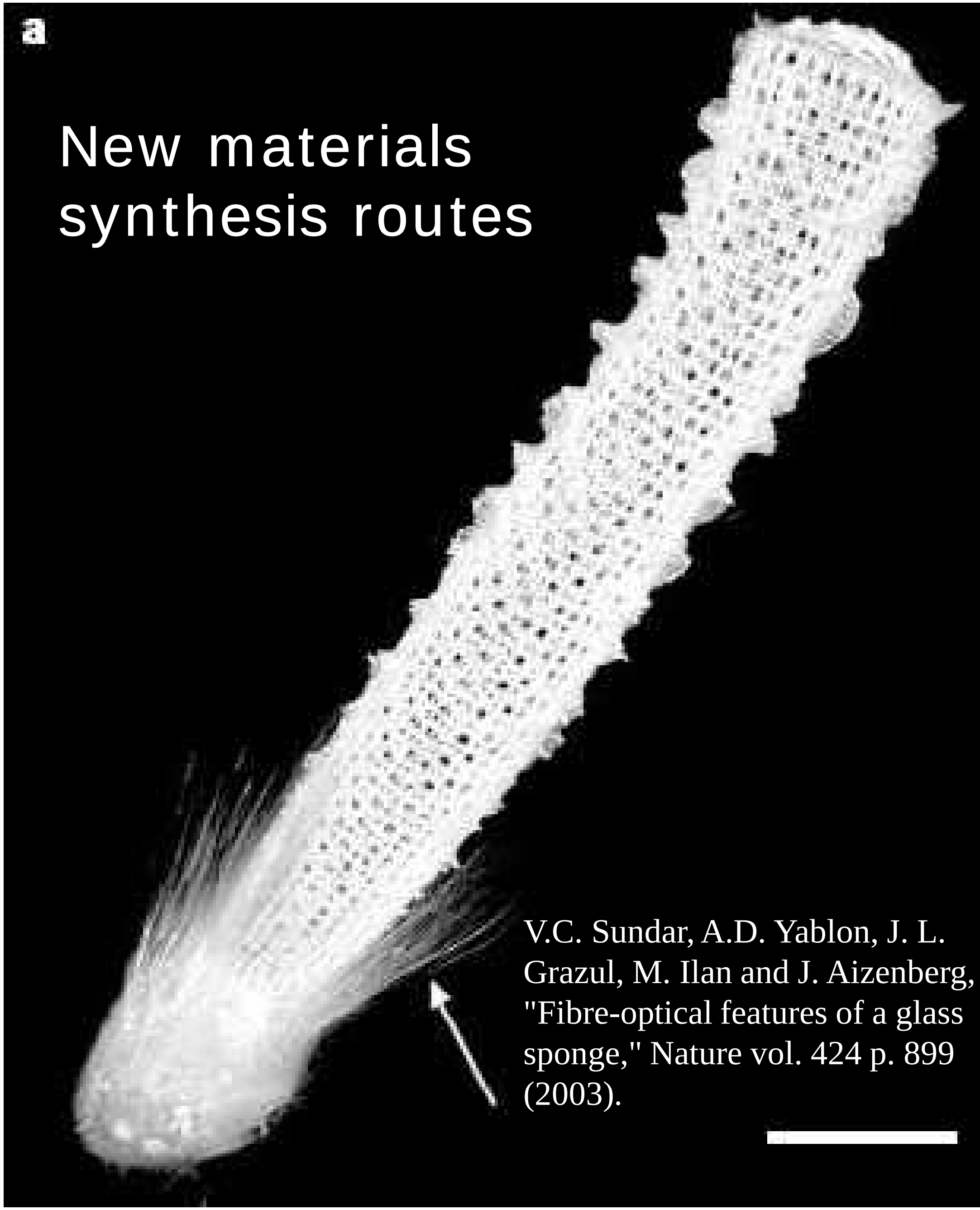


Institute for Molecular Manufacturing
http://www.imm.org/

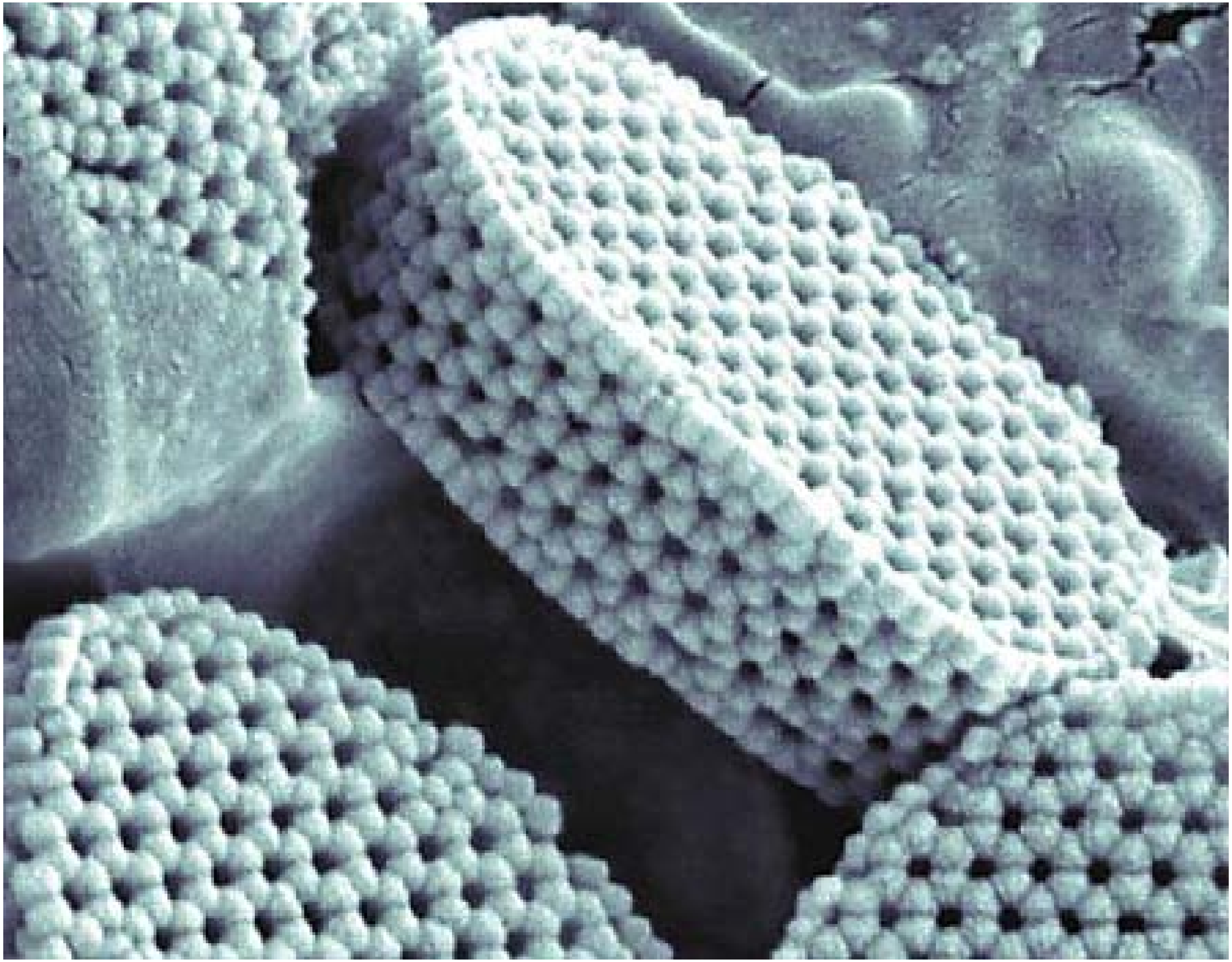
New materials synthesis routes



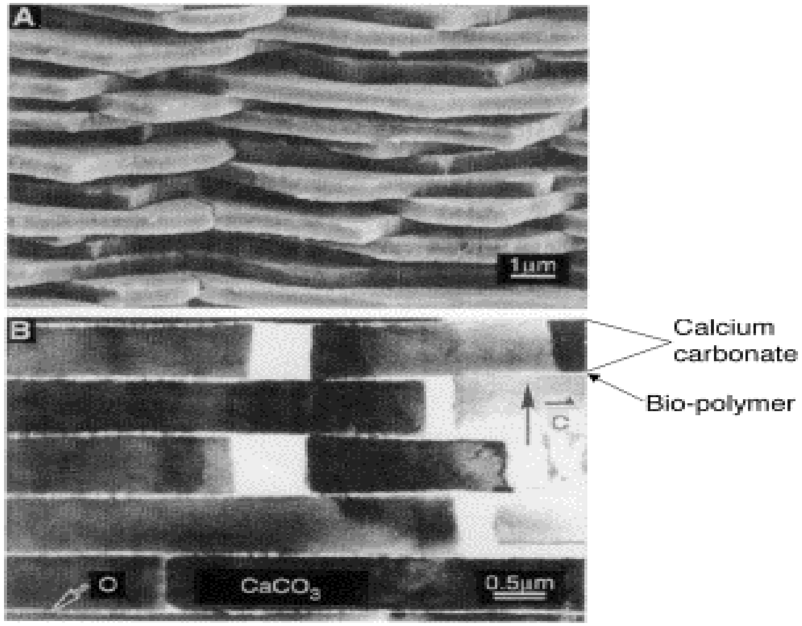
Produced at room temperature from sunlight and seawater.



V.C. Sundar, A.D. Yablon, J. L. Grazul, M. Ilan and J. Aizenberg, "Fibre-optical features of a glass sponge," Nature vol. 424 p. 899 (2003).

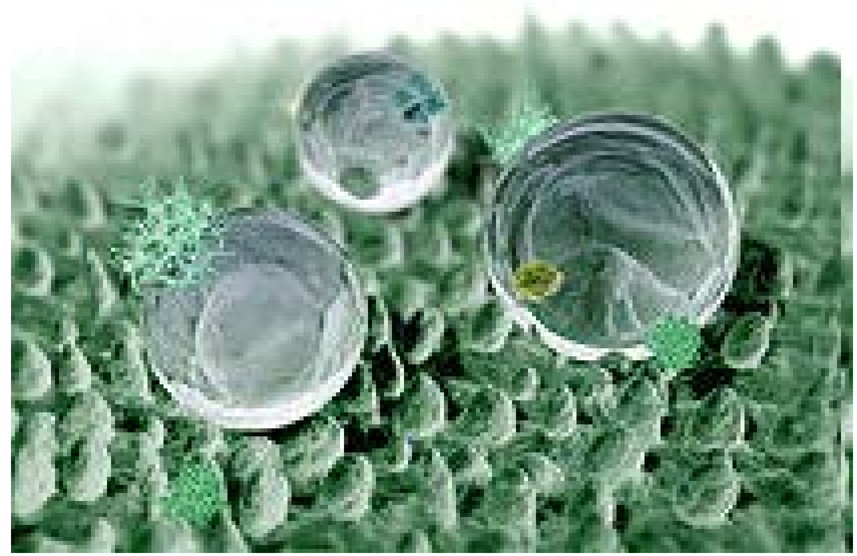


Tough materials



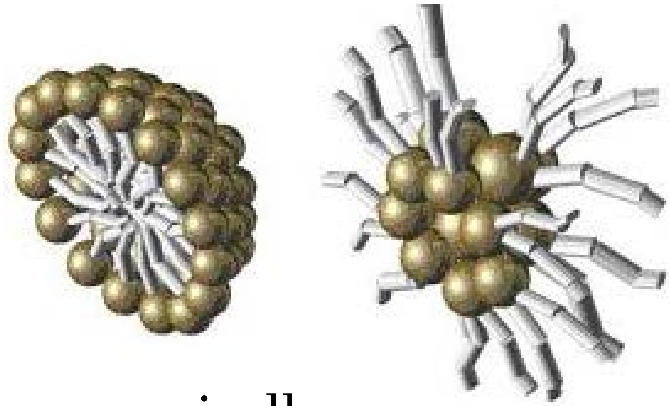
http://www.mrti.utep.edu/Full%20Pages/selfass.htm

Lotus effect

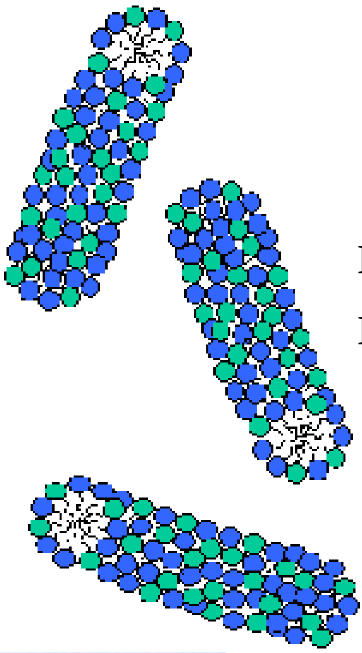


Reversible glue

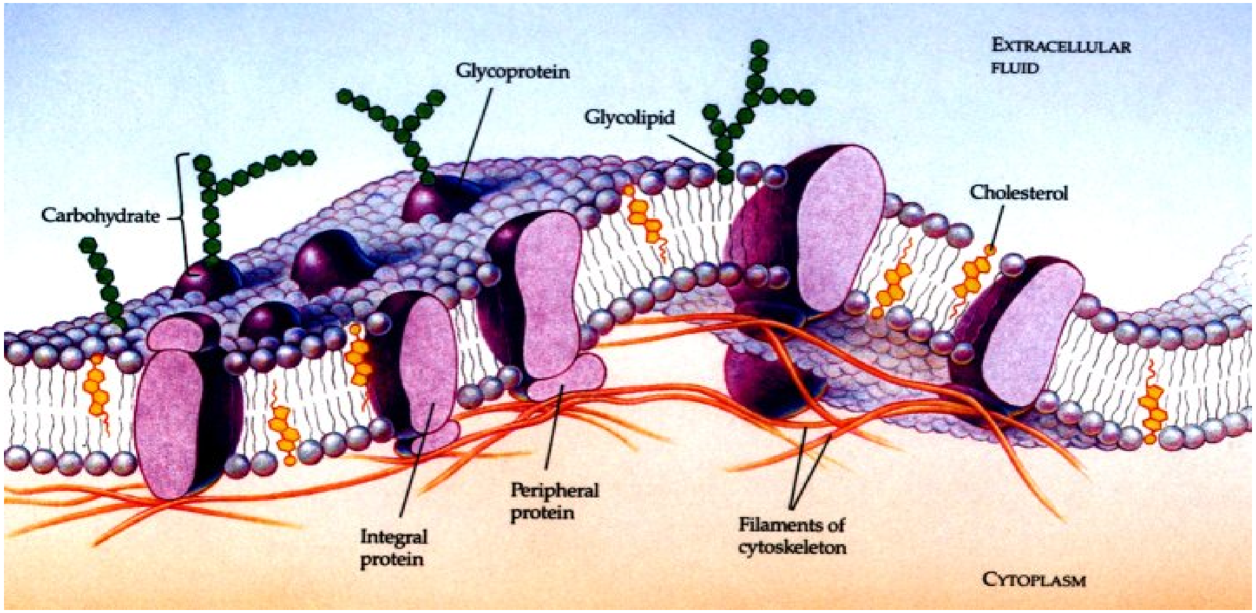
Self-Assembly



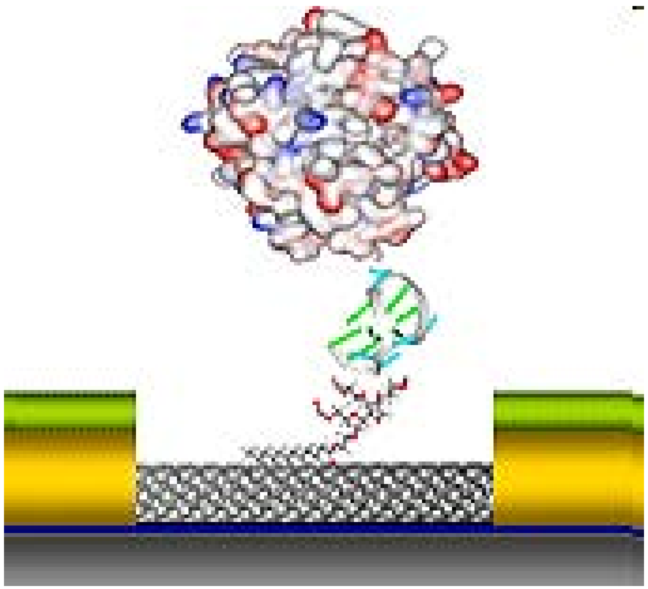
micelles



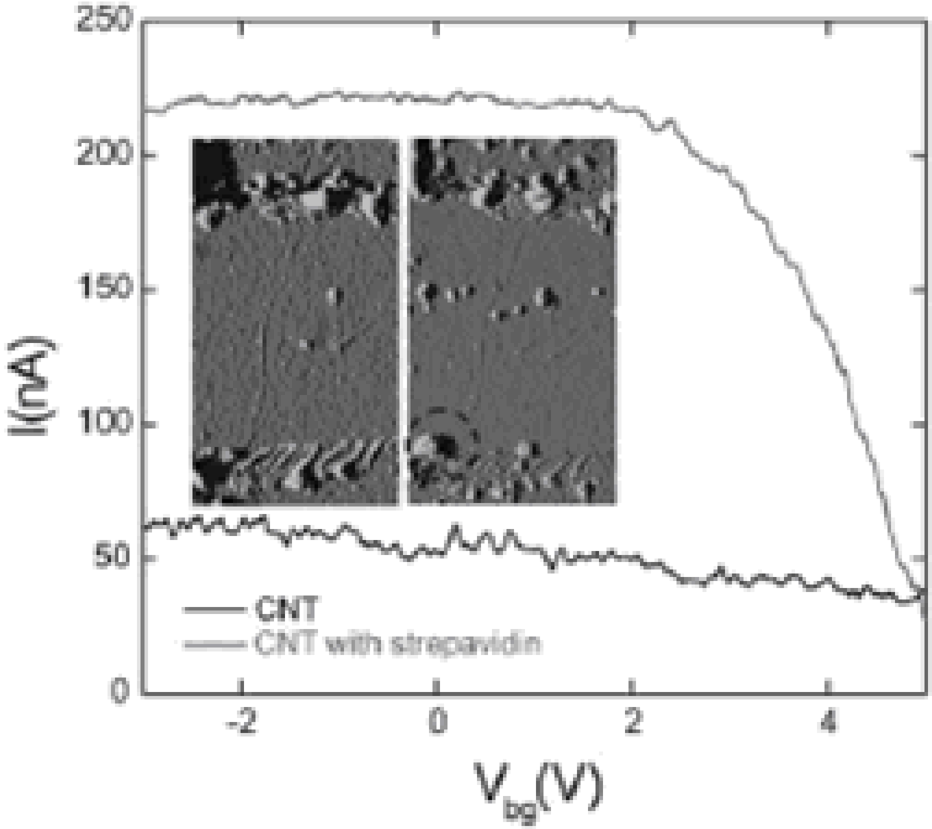
rod like
micelles



Aptamers

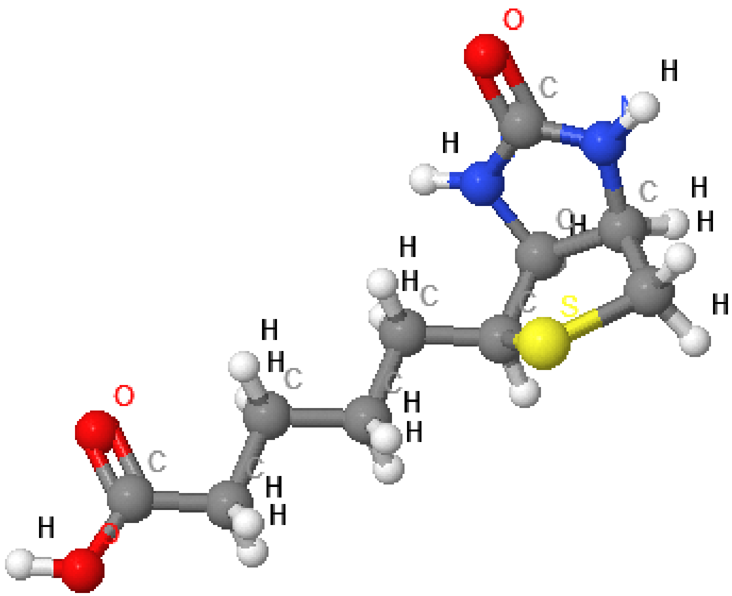


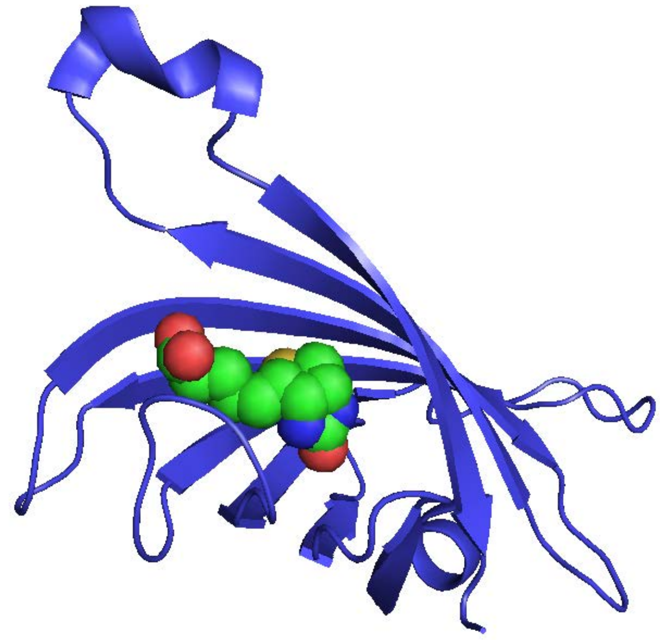
Jeong-O Lee, KRICT



Molecular recognition

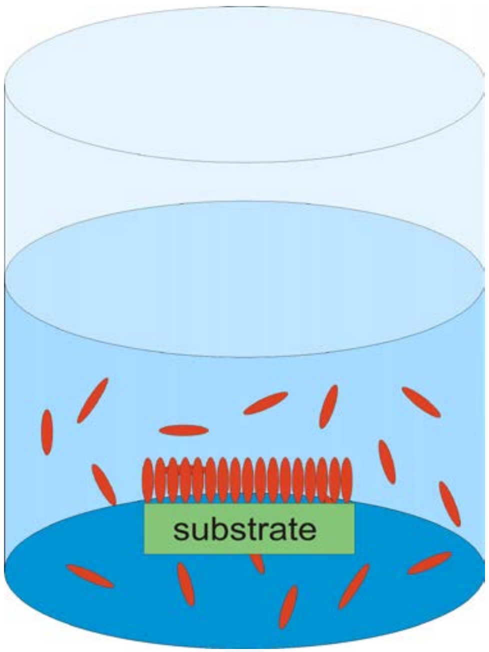
Biotin - Streptavidin

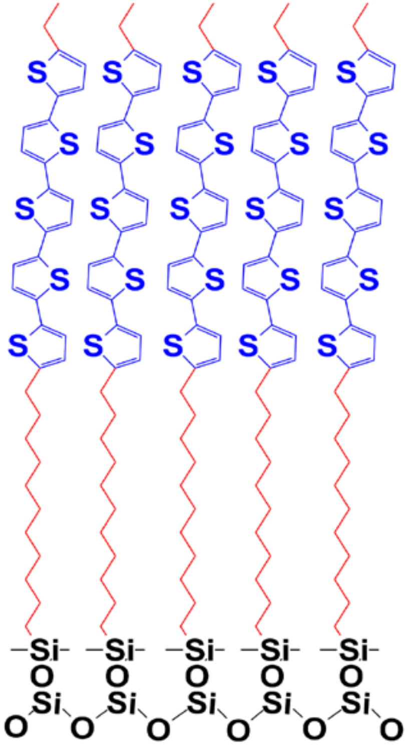


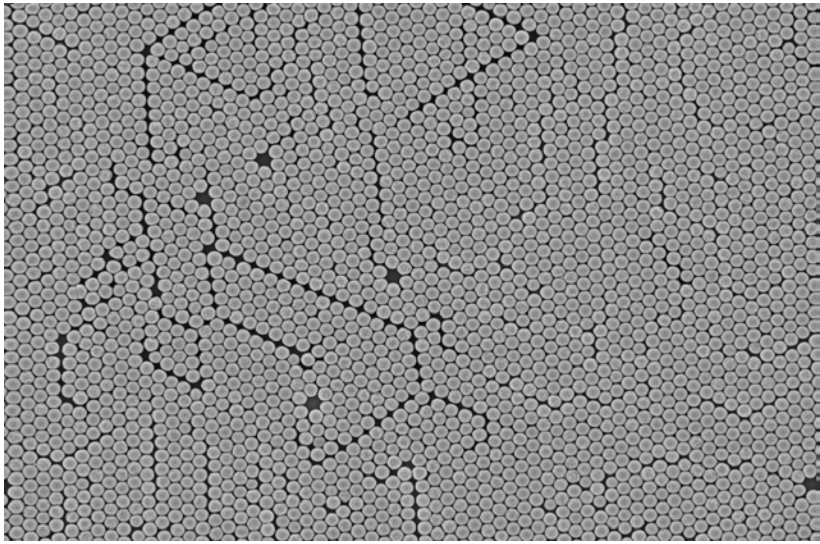


Self-assembly

The future of efficient electronics manufacturing lies in using more self-assembly.

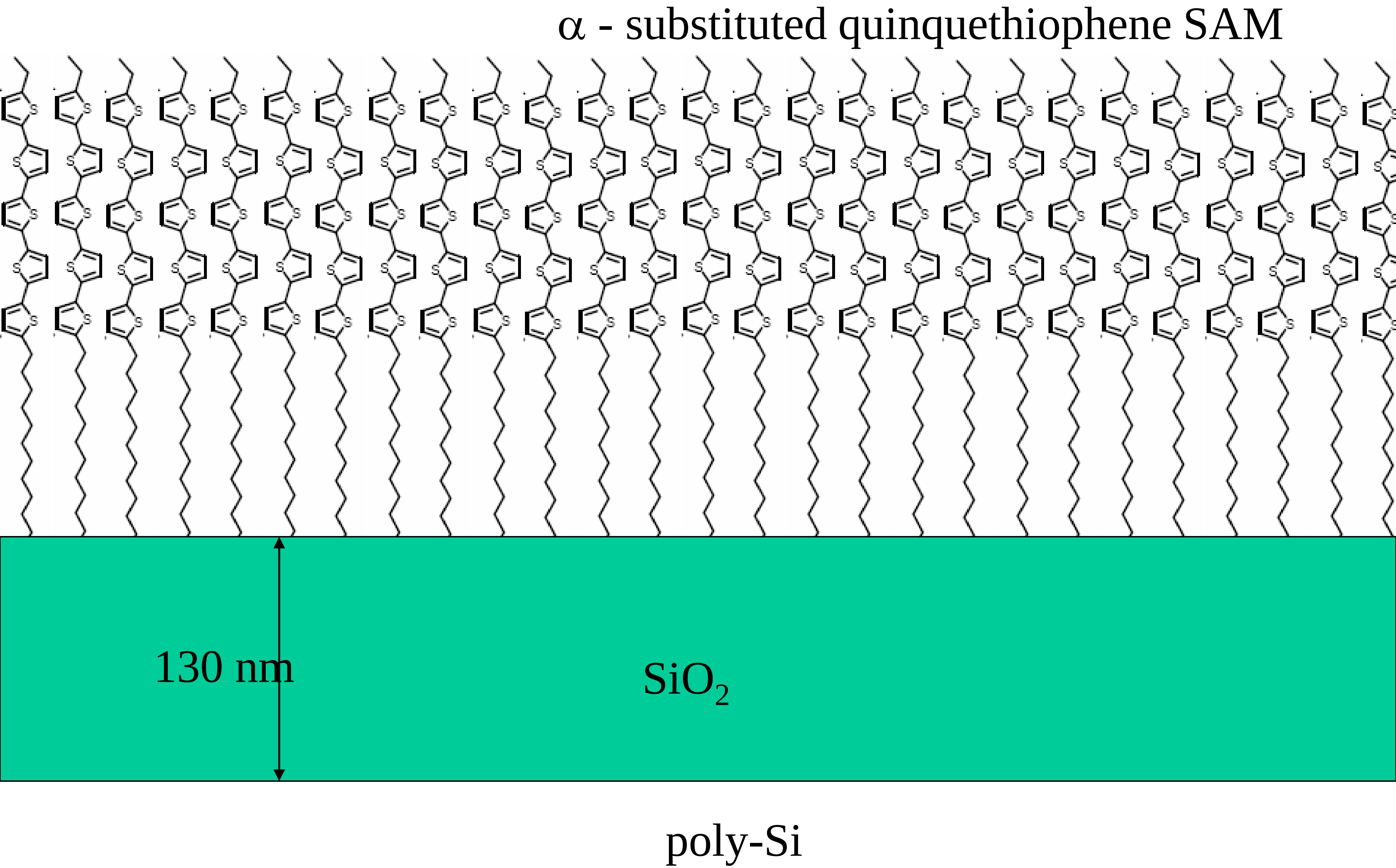






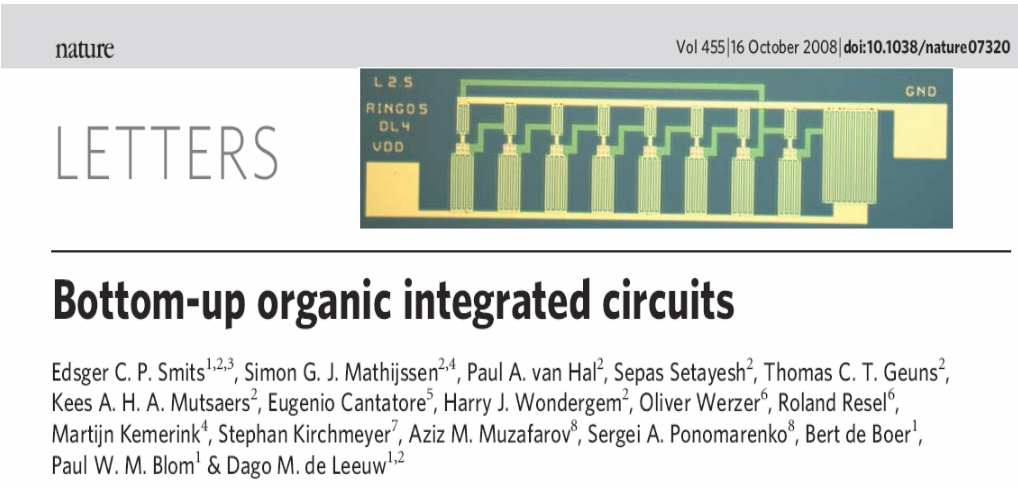
polystyrene spheres with a diameter of 500 nm

Bottom-up Organic Integrated Circuits



Organic Integrated Circuits

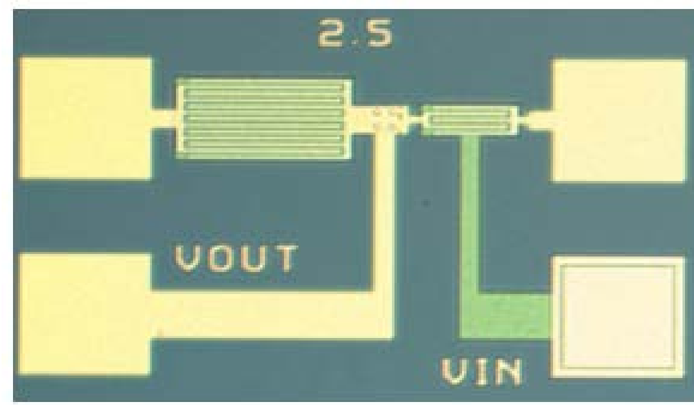
inverter
ring oscillator
code generator with 300 transistors


nature
Vol 455|16 October 2008|doi:10.1038/nature07320

LETTERS

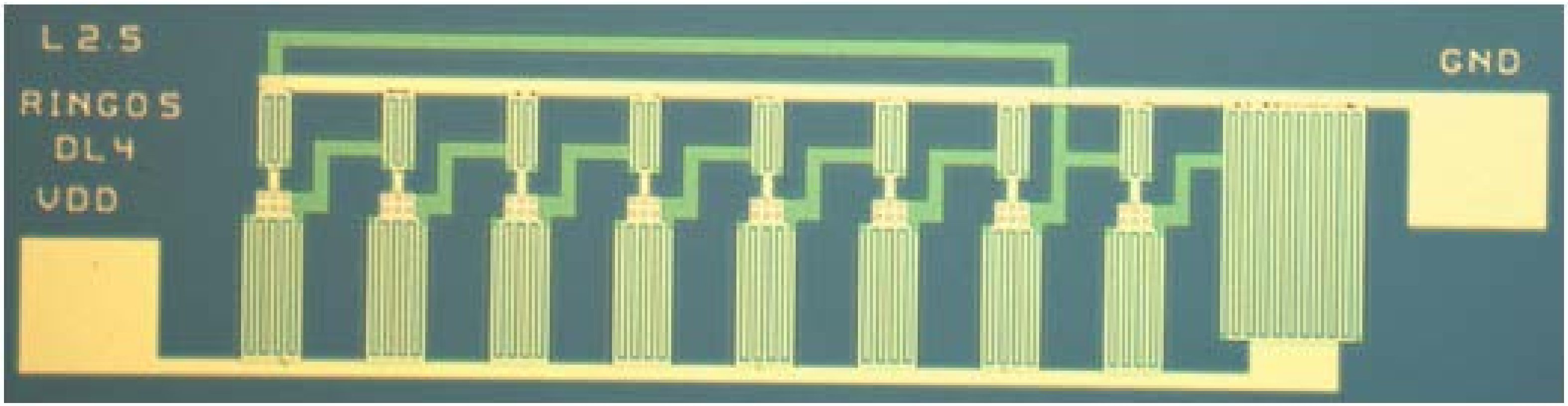
Bottom-up organic integrated circuits

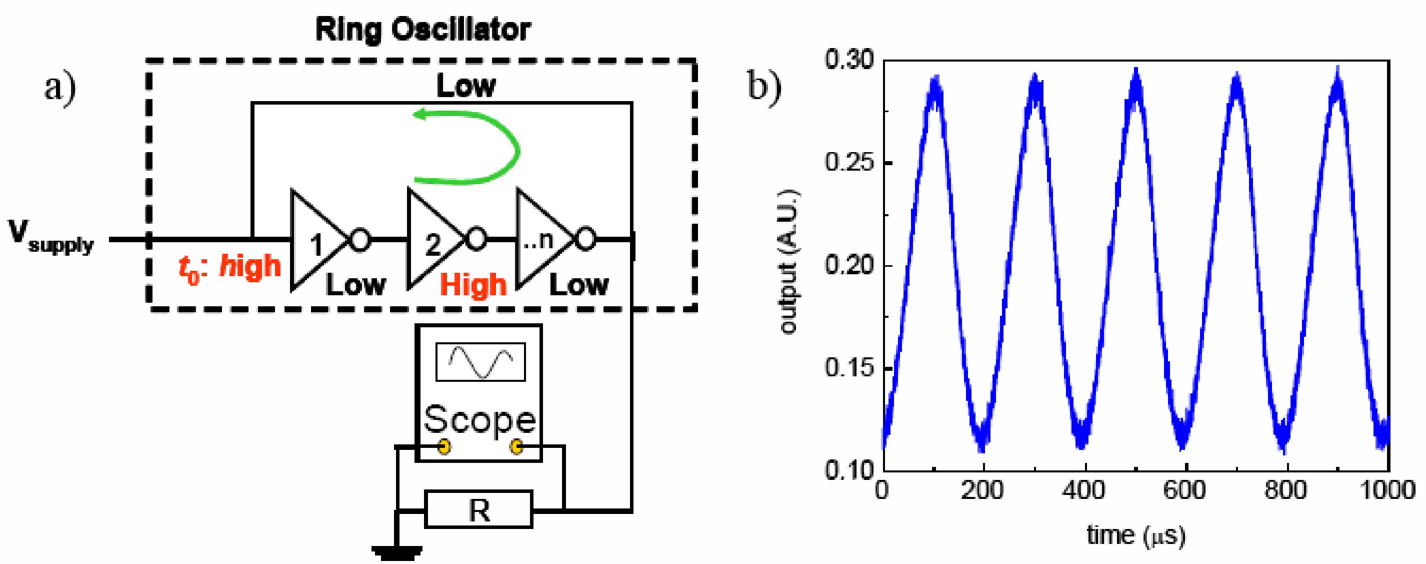
Edsger C. P. Smits[1,2,3], Simon G. J. Mathijssen[2,4], Paul A. van Hal[2], Sepas Setayesh[2], Thomas C. T. Geuns[2], Kees A. H. A. Mutsaers[2], Eugenio Cantatore[5], Harry J. Wondergem[2], Oliver Werzer[6], Roland Resel[6], Martijn Kemerink[4], Stephan Kirchmeyer[7], Aziz M. Muzafarov[8], Sergei A. Ponomarenko[8], Bert de Boer[1], Paul W. M. Blom[1] & Dago M. de Leeuw[1,2]



E. C.P. Smith, et al., Nature (2008)
S. G. J. Mathiessen, Nature Nanotechnology (2009)
F. Gholamrezaie, Nanoletters (2010)

Bottom-up Organic Integrated Circuits

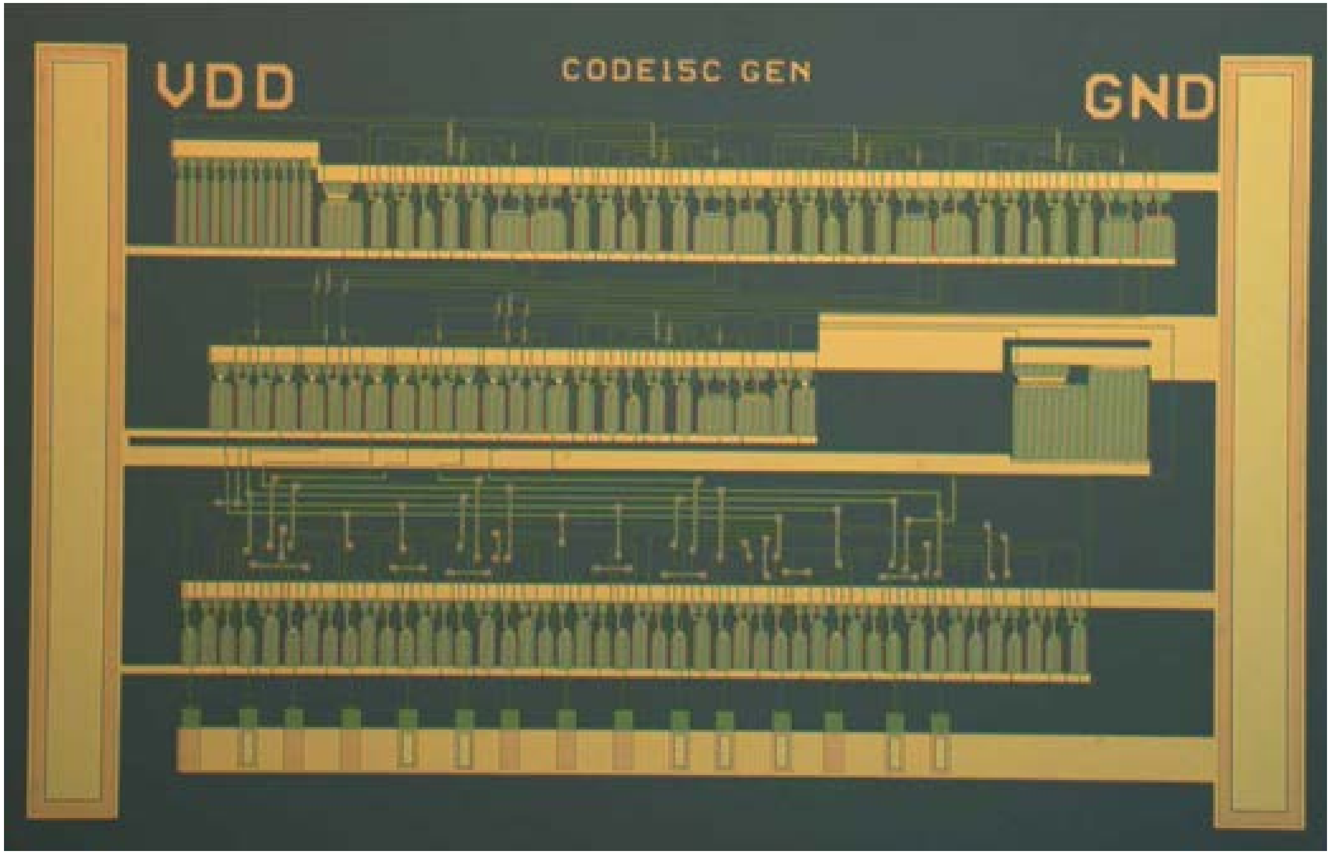




Nature 455, pp. 956-959 (2008)

Bottom-up Organic Integrated Circuits

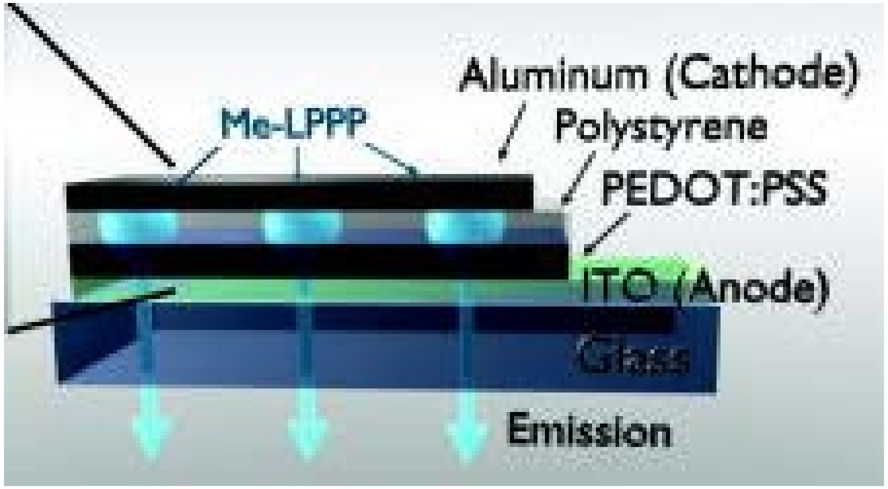
15 bit code generator

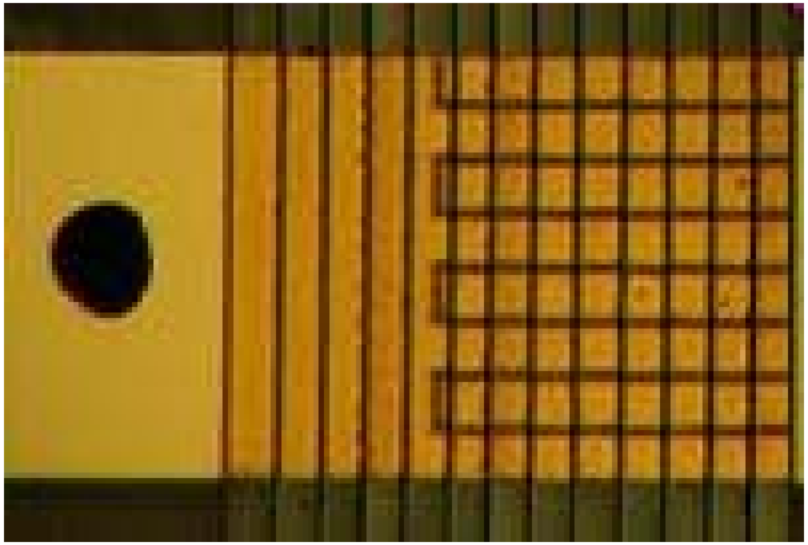


300 SAMFETs

Solution processed devices

Emil List





Semiconductor nanosphere methyl-substituted laddertype poly(*para*-phenylene) OLEDs

Appl. Phys. Lett. 92, 183305 (2008)

Photo detectors of inkjet printed HgTe semiconducting nanocrystals

Advanced Materials 19 pp. 3574 - 3578 (2007)

Solution processed inorganic devices

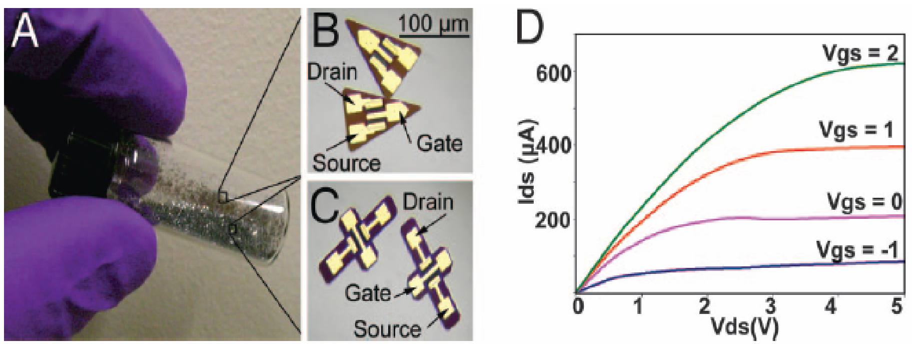
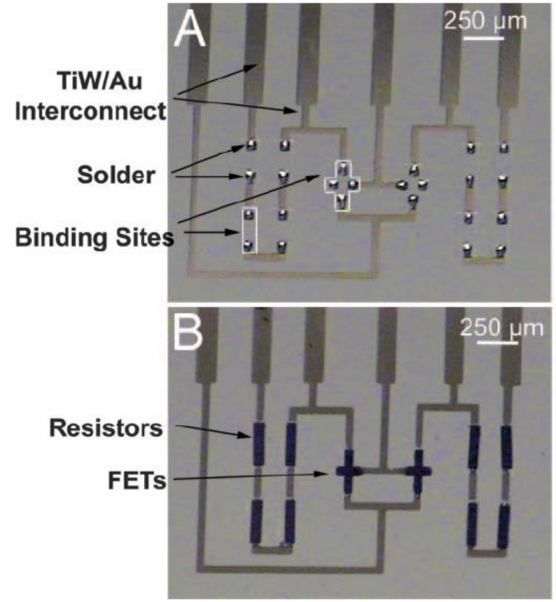


Fig. 4. Released silicon FETs. (*A*) A collection of freestanding single-crystal silicon FETs. (*B* and *C*) Optical microscope images of and triangle-shaped (*B*) cross-shaped (*C*). (*D*) Measured performance of a typical triangular transistor before release from SOI wafer.



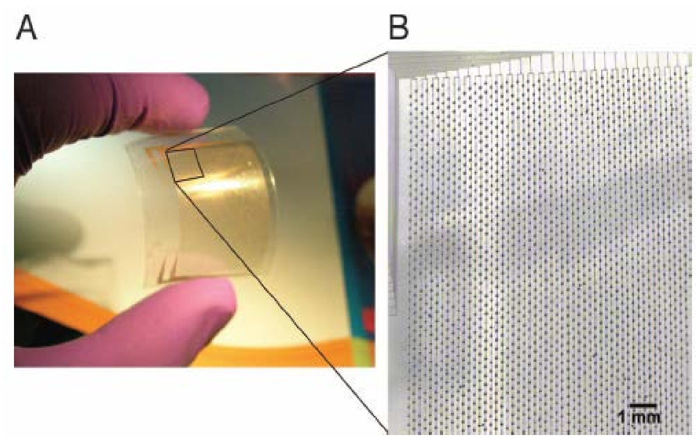
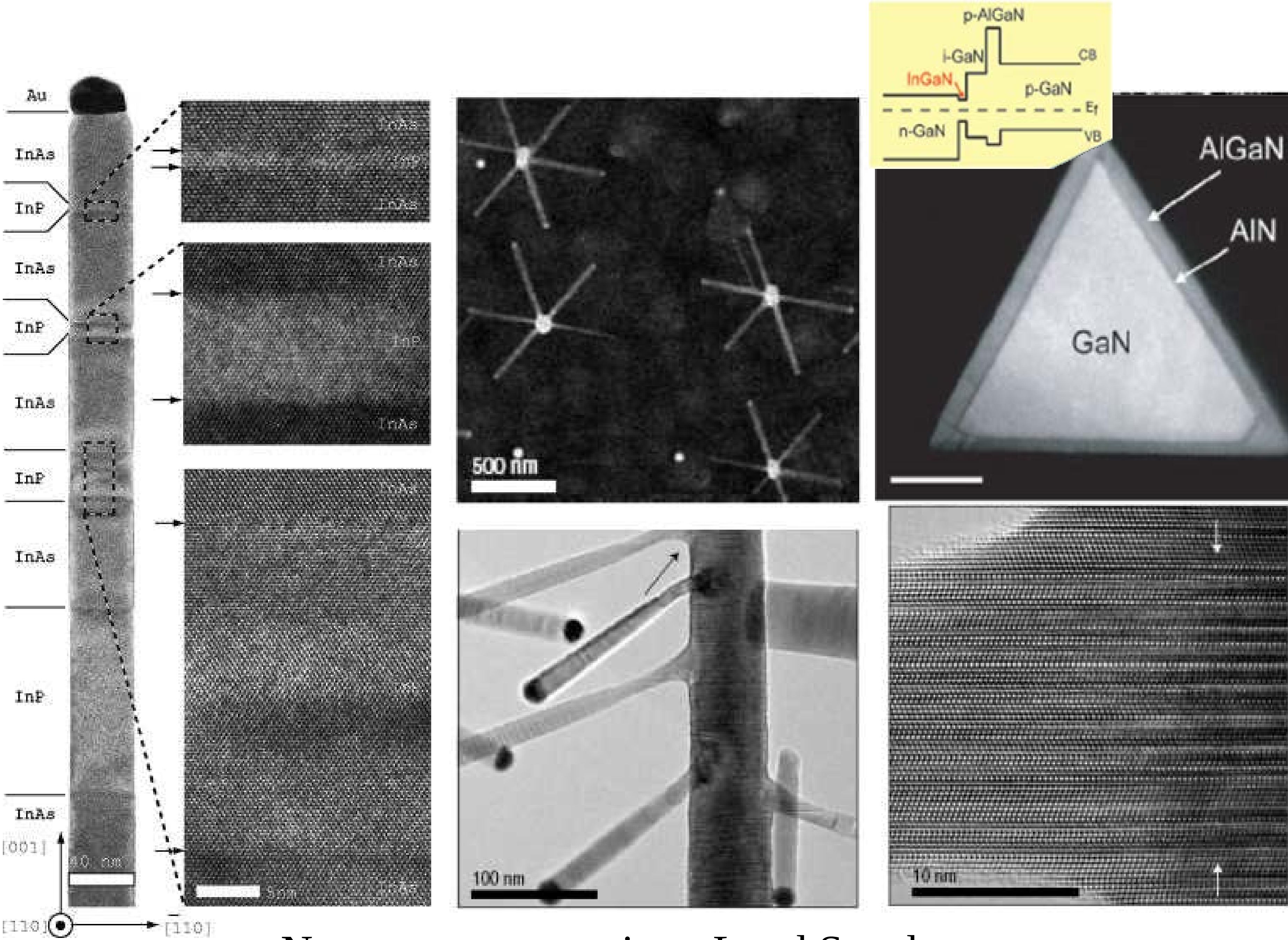


Fig. 8. High yield (≈97%) self-assembly of 100-µm, circular, single-crystal silicon elements onto a flexible plastic template containing 10,000 binding sites. (*A*) Completed template. (*B*) Close-up image of ≈2,000 binding sites, self-assembled elements, and electrical interconnects.

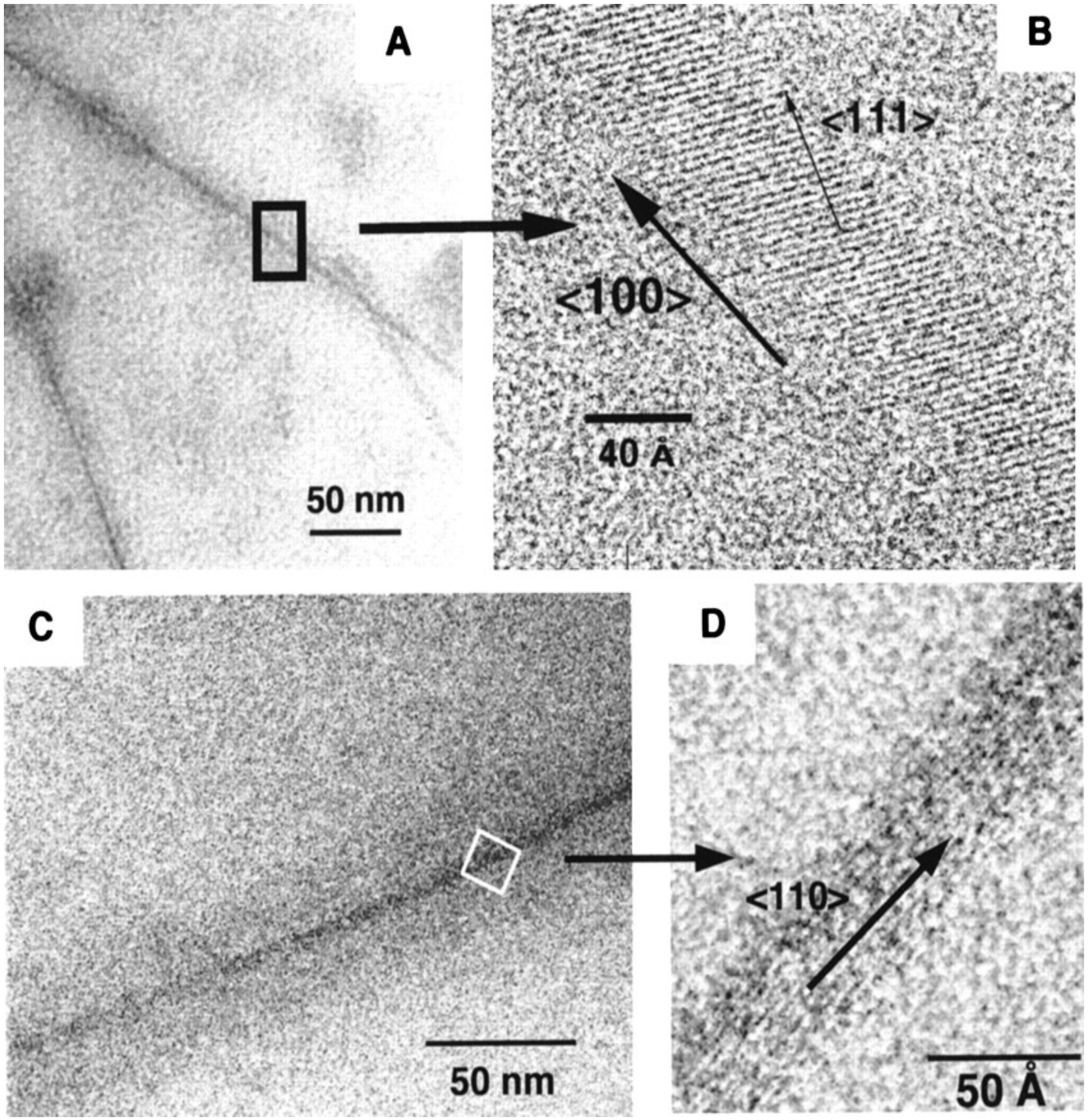
PNAS | September 19, 2006 | vol. 103 | no. 38 | 13925

Sean A. Stauth and Babak A. Parviz, PNAS vol. 103 pp. 13922–13927 (2006)



Nanometer consortium, Lund Sweden

Solution-Grown Silicon Nanowires



Control of Thickness and Orientation of Solution-Grown Silicon Nanowires, Justin D. Holmes, Keith P. Johnston, R. Christopher Doty, Brian A. Korgel, Science 287. pp. 1471 - 1473 (2000).

Si, Ge, ZnO, CdTe, CdSe

Self-assembly of devices will be a key competence

- Self organization of structures from 100 microns to 0.1 nm
- Learn chemistry from biology
- Exploit biological infrastructure
  - Trees = self assembled solar cells, batteries
- Self assemble lithographically produced devices
  - lighting panels