NanoElectronics

BIOLOGICAL MOLECULES IN DEVELOPING ELECTRONIC DEVICES

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Nanoelectronics is where physics, material science, chemistry and electric engineering inevitably meet.

OUTLOOK

✓ INTRODUCTION

✓ SELF-ASSEMBLED NANOSTRUCTURES. DNA AND NANOELECTRONICS

1 - TEMPLATE FOR CONSTRUCTING NANOCIRCUITS;

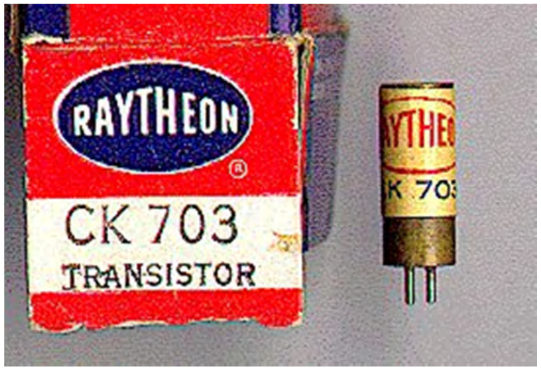
2 - THE POTENTIAL TO PERFORM CALCULATIONS;

3 - COMPUTATIONAL CIRCUIT; LOGIC GATE.

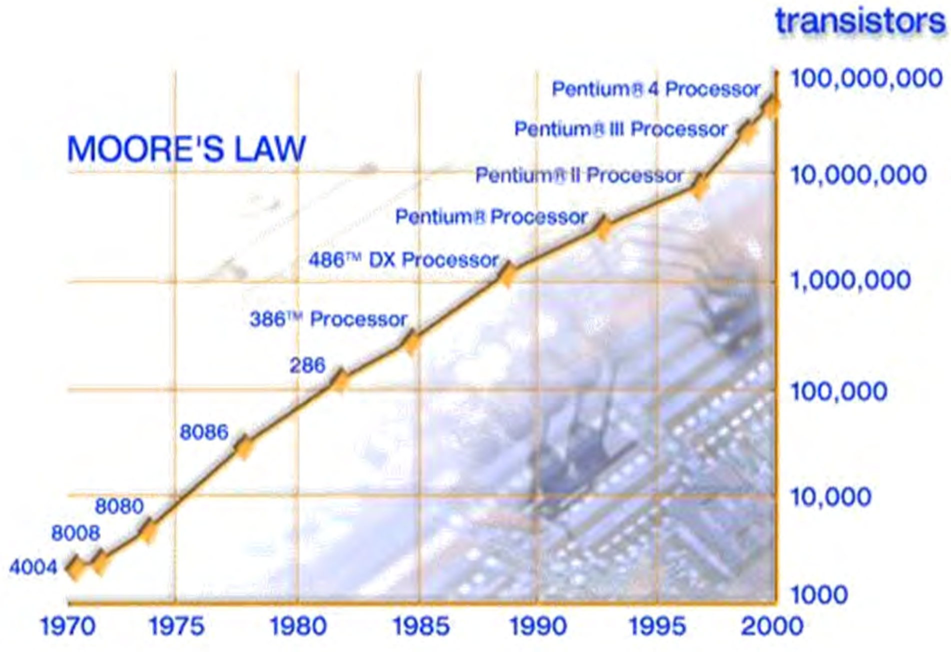
✓CONCLUSION

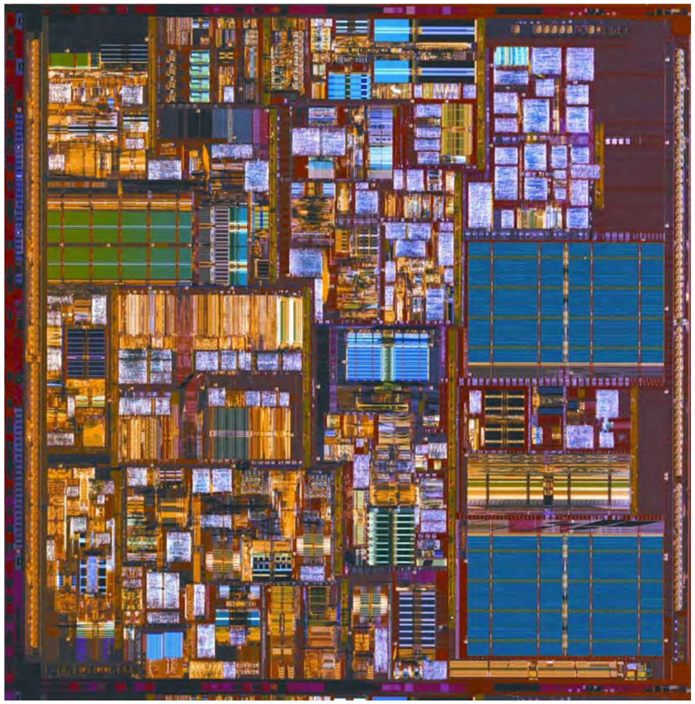
DEVELOPMENT OF SEMICONDUCTOR DEVICES

✓BASES OF IC - metal-oxide-semiconductor (MOS) field-effect transistor (FET)



First commercial point contact transistor (1948)



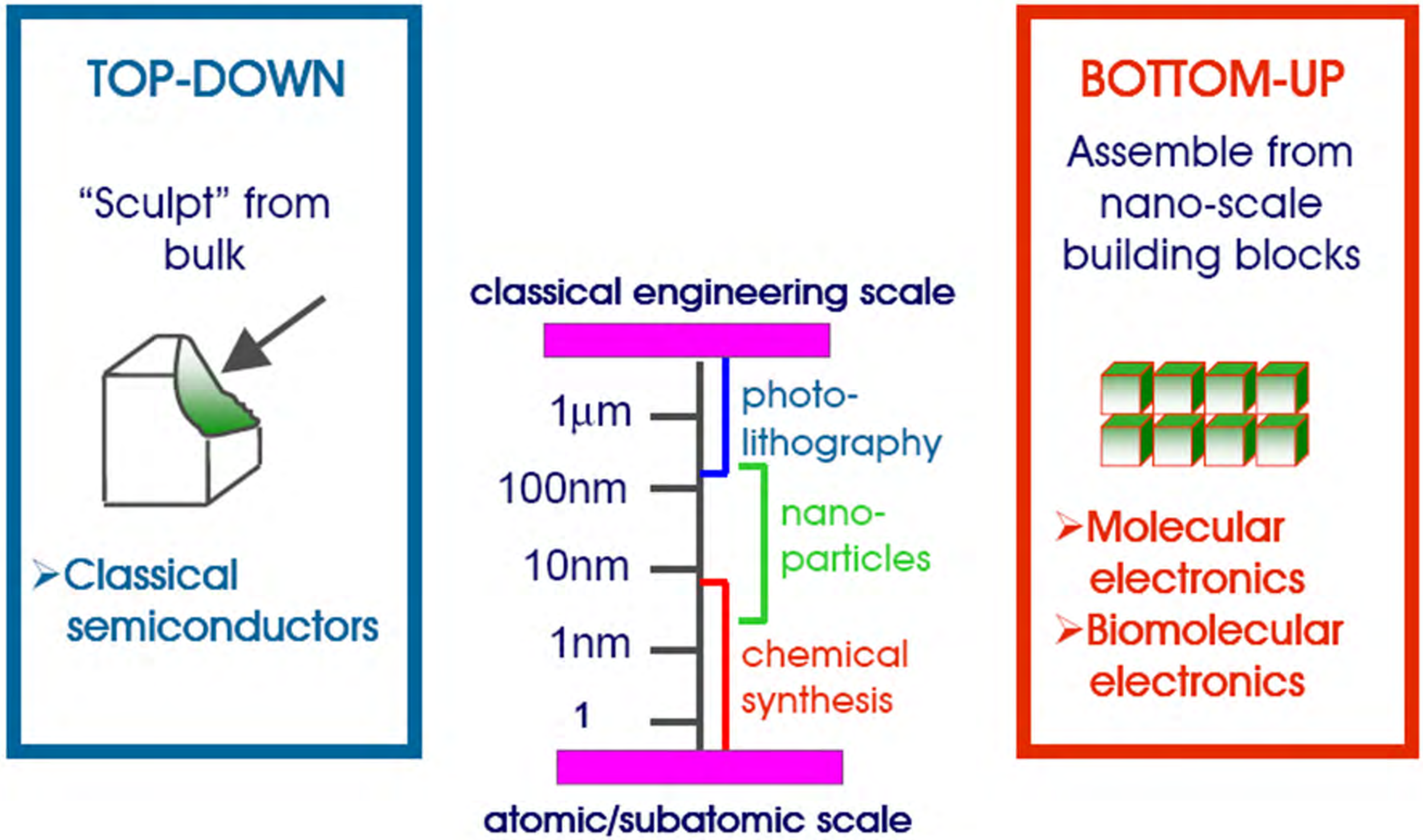


Layout *Pentium* chip (2006)
55 ×10^9 transistors (~1.3 µm)

MOSFET

3 nm (for RAM) < hSiO2 < 5 nm (for ROM)

LIMITING FACTOR – The horizontal size



Denser devices scaling down MOSFETs to a gate length < 20 nm

- failure of the current driving capacity;
- thermal fluctuations;
- tunneling through the junction
- power dissipation

(BIO) MOLECULAR ELECTRONICS

- nanotechnology have already been achieved by biological systems
- machinery to "self-assemble" artificial structures

SELF-ASSEBLED NANOSTRUCTURES; DNA IN NANOELECRONICS

Why Use DNA to Build Devices?

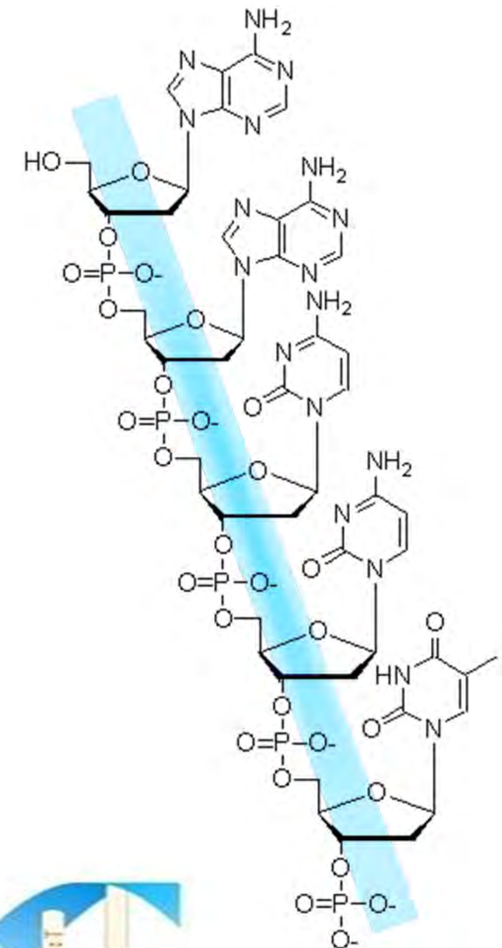
✓Molecules self-assemble to their minimum energy configuration;

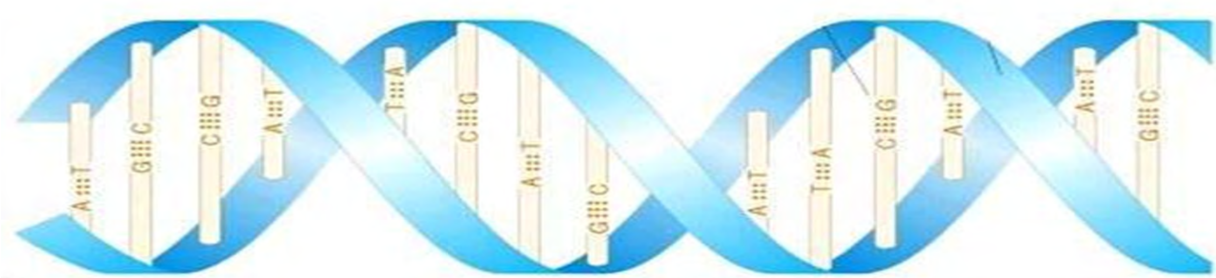
✓Molecules form stable structures;

✓Control of DNA structure through its nucleotide sequence;

✓Control of molecular interactions through sticky ends;

✓Very small size (~ 2 nm in diameter).



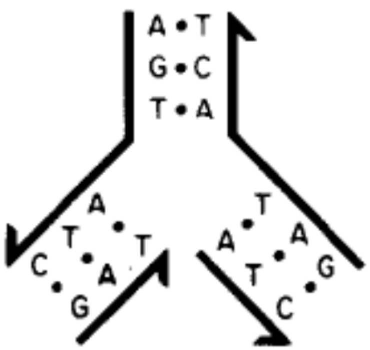


TEMPLATE FOR CONSTRUCTION OF ELECTRICAL CIRCUITS

CONTROL OF DNA STRUCTURE

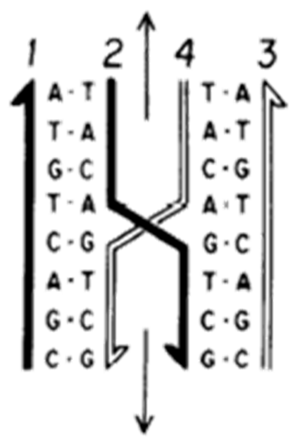
✓DNA replication

✓replication fork
✓*helicases* separates the strands

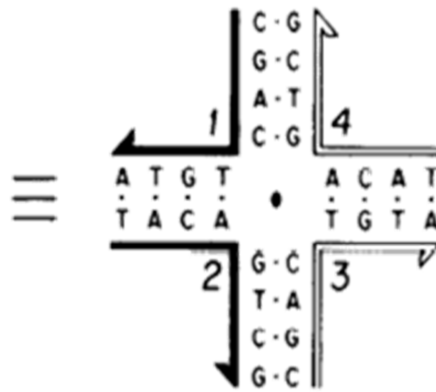


✓ Formation of junctions

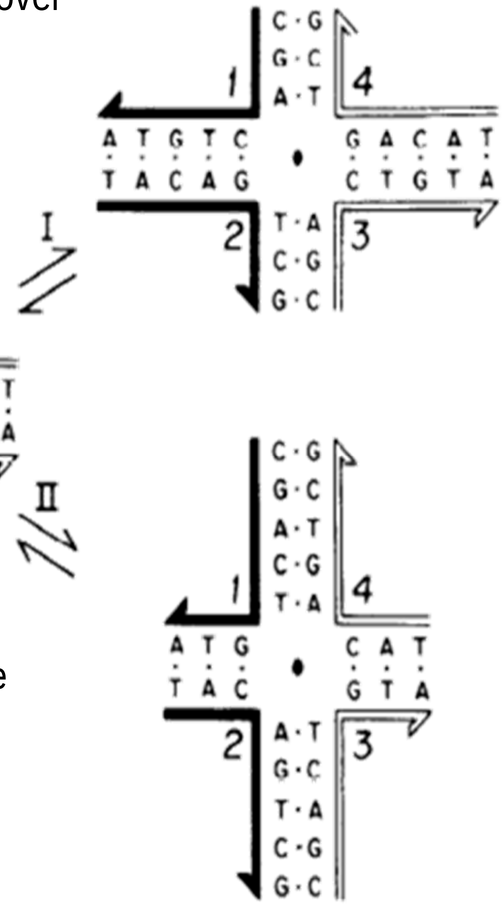
✓*recombinases* allows the crossover



Holliday junction
genetic recombination



Cruciform structure
gene expression

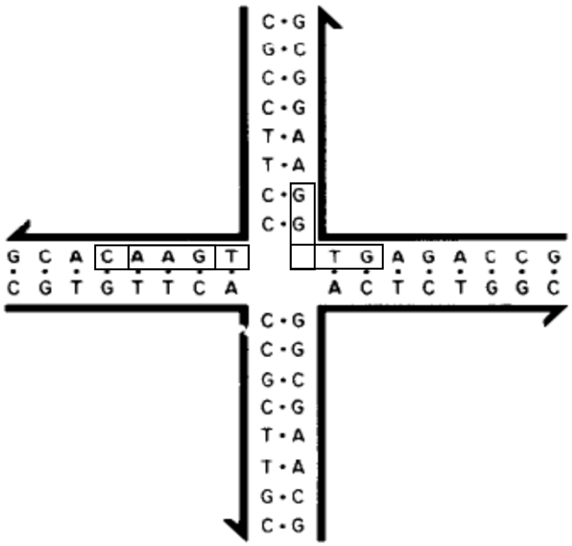


Mechanisms driven by enzymes.
Unlikely to occur only mixing ODN.

N.C. Seeman, J. Theor. Biol., 99(1982)237

TEMPLATE FOR CONSTRUCTION OF ELECTRICAL CIRCUITS

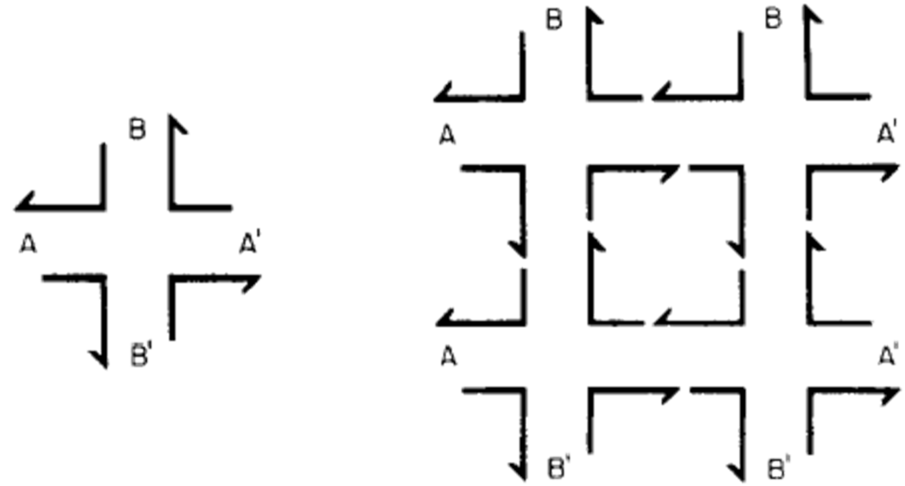
IMOBILE JUNCTION

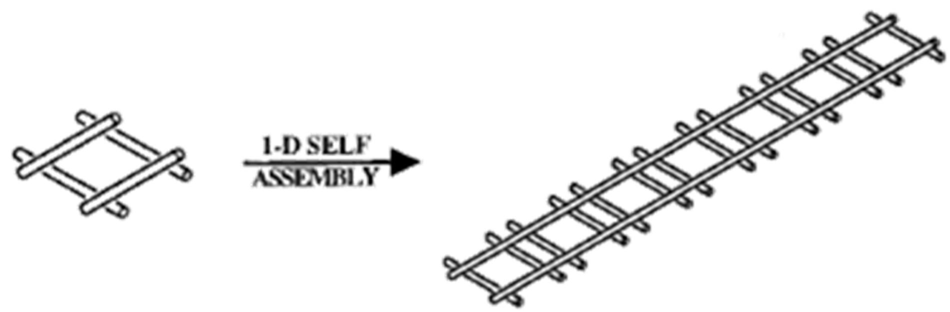


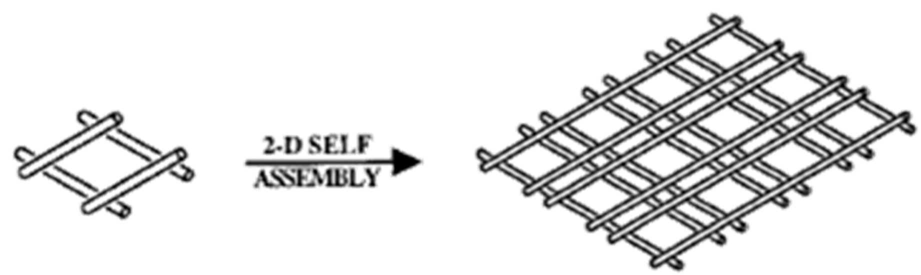
- Each criton must be unique
- The anti-criton spanning a bend must not be present in any strand
- Self-complementary critons not allowed
- The same base pair can only abut the junction twice and must not be on adjacent arms.

N.C. Seeman, J. Theor. Biol., 99(1982)237
C. Mao, W. Sun, N.C. Seeman, J. Am. Chem. Soc., 121(1999)5437

NETWORKS



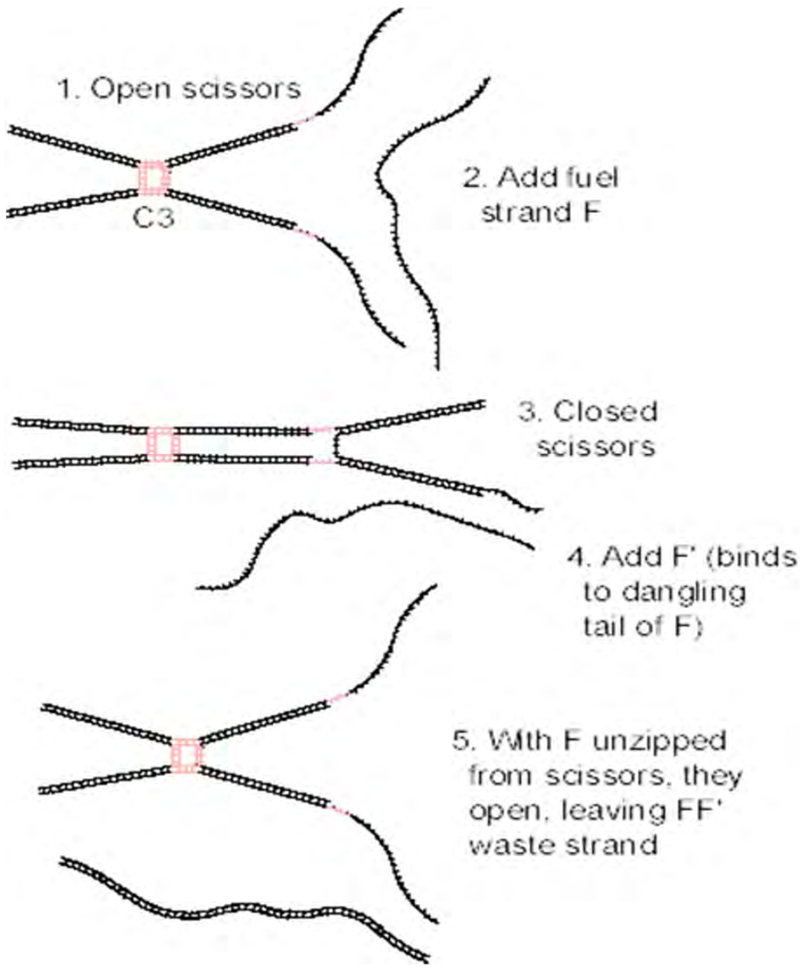




TEMPLATE FOR CONSTRUCTION OF ELECTRICAL CIRCUITS

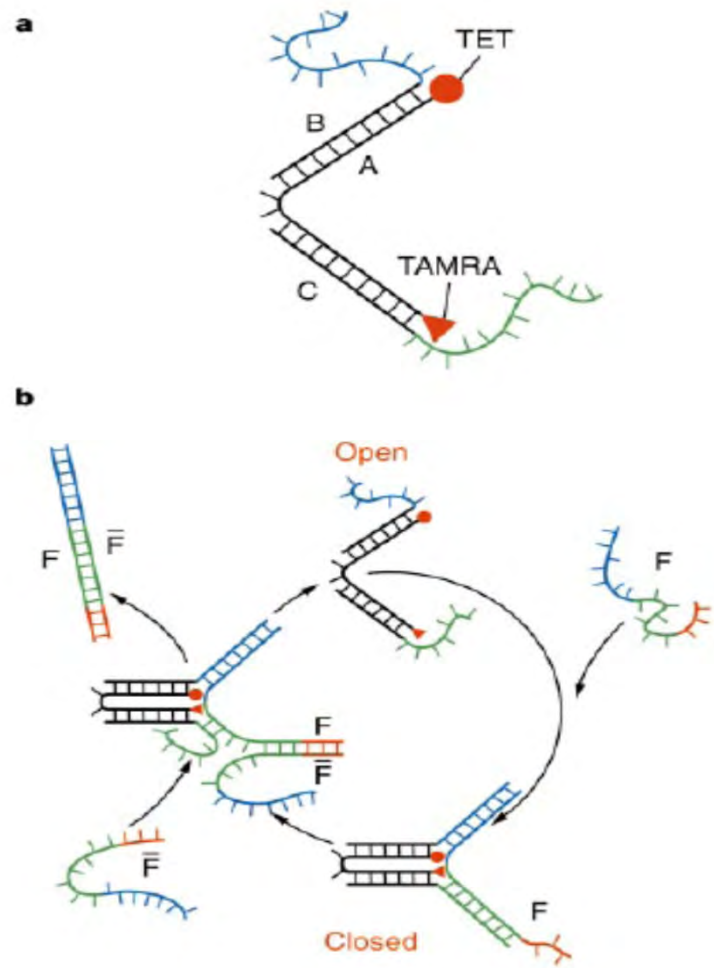
✓*Molecular motors - transfer of molecule free energy and removal of strand into mechanical action*

<u>DNA *Scissor*</u>



F. C. Simmel, B. Yurke, H. S. Nalwa, ed., American Scientific Publishers, Vol. 2, 495-504 (2004).

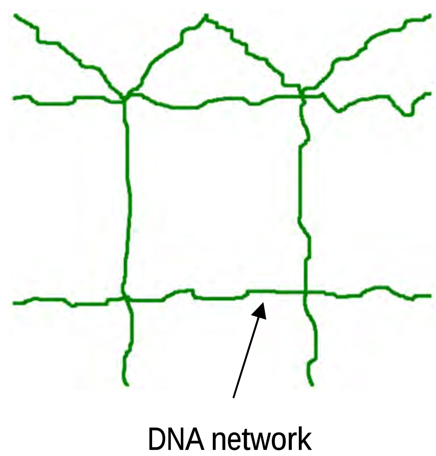
<u>DNA *Tweezer*</u>



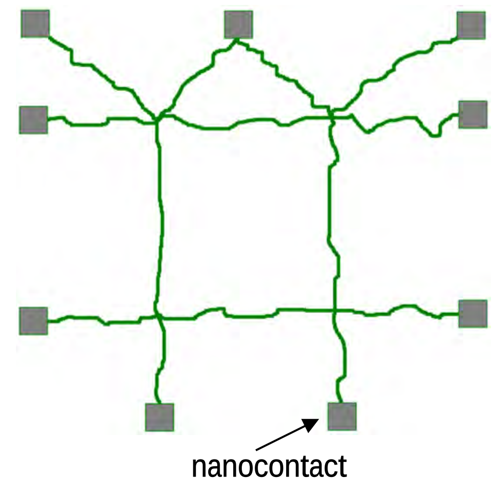
B. Yurke et al., Nature, 406 (2000) 605

TEMPLATE FOR CONSTRUCTION OF ELECTRICAL CIRCUITS

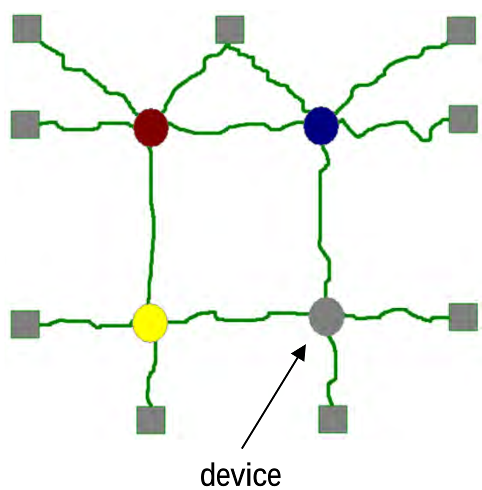
a) assembly of DNA into networks



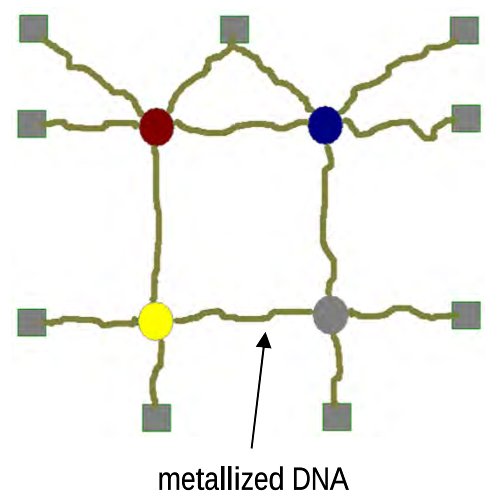
b) integration into a contact array



c) functional elements must be positioned



d) mettalization



ELECTRICAL CONDUCTION THROUGH DNA

INSULATOR

• 16 µm-long λ-DNA, 12-16 µm-spaced electrodes, single molecule

Braun et al., Nature, 391 (1998) 775.

✓Template for conducting Ag nanowires

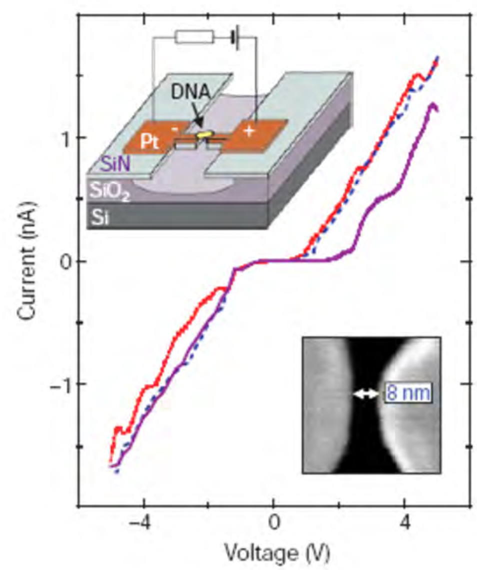
• 1.8 µm-long λ-DNA, SFM, single molecule

de Pablo et al., Phys. Rev. Lett., 85 (2000) 4992

SEMICONDUCTOR

•10.4 nm-long (30 bp) poly(G)-poly(C), 8 nm-spaced electrodes

Porath et al., Nature, 403 (2000) 635



CONDUCTOR

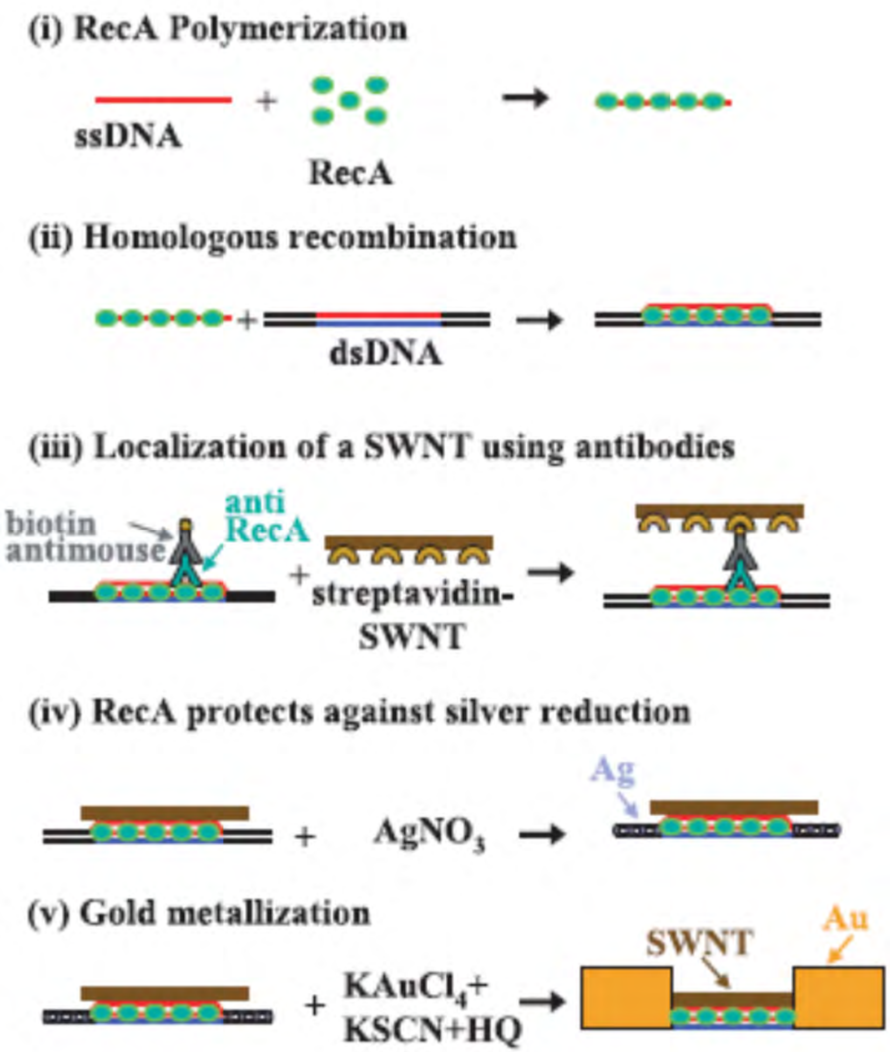
•600 nm-long λ-DNA, bundels in 2 nm hole

Fink and Schonenberg, Nature, 398 (1999) 6726

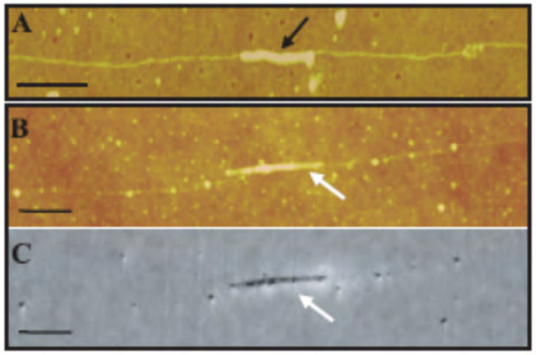
✓ coherent tunelling (no energy exachange)

✓ thermal hopping between separated G.C base pairs

DNA TEMPLATED CNFET



(i) RecA (*E. Coli*) monomers polymerize on a ssDNA molecule to form a nucleoprotein filament.
(ii) Homologous recombination reaction leads to binding of the nucleoprotein filament at the desired address on an aldehydederivatized scaffold dsDNA molecule.
(iii) The DNA-bound RecA is used to localize a streptavidin-functionalized SWNT, utilizing a primary antibody to RecA and a biotin-conjugated secondary antibody.
(iv) Incubation in an AgNO3 solution leads to the formation of silver clusters on the segments that are unprotected by RecA.
(v) Electroless gold deposition, using the silver clusters as nucleation centers, results in the formation of two DNA-templated gold wires contacting the SWNT bound at the gap.



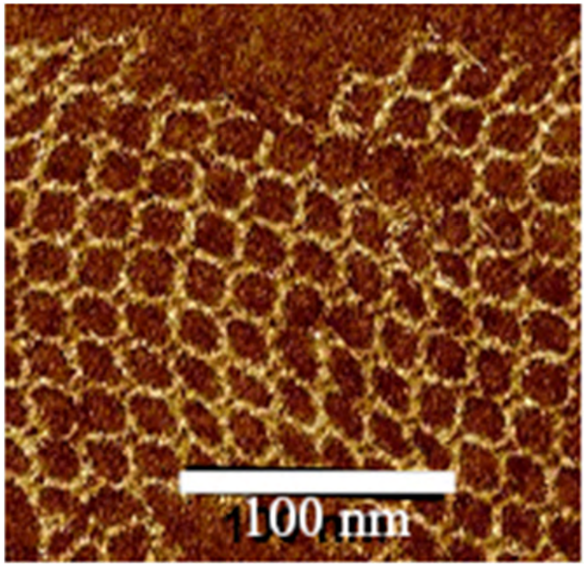
AFM of (ii)

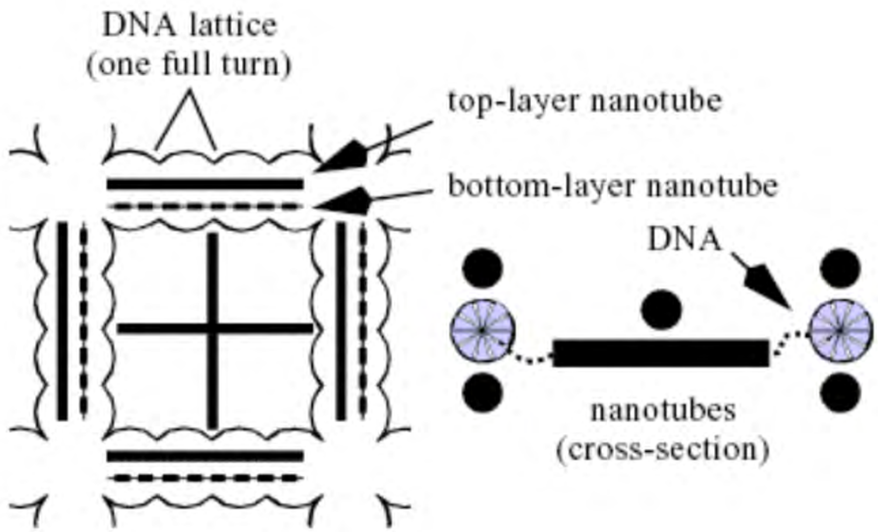
AFM of (iii)

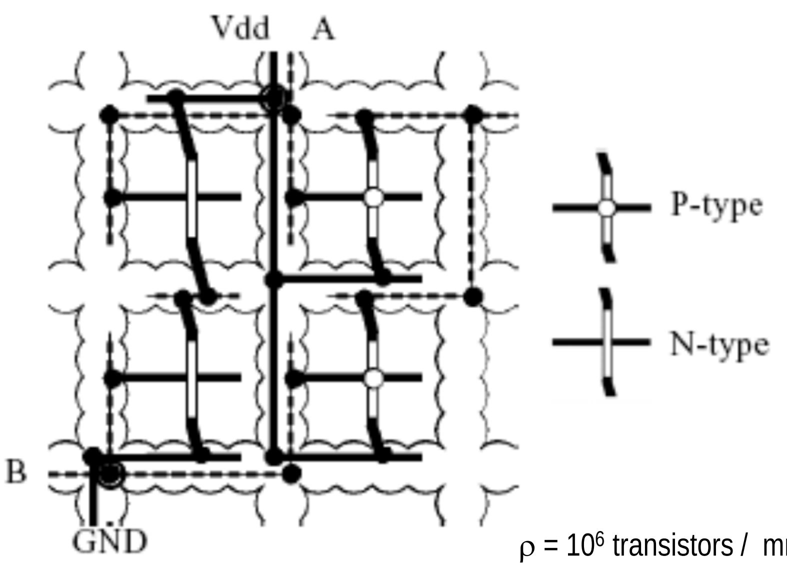
Scanning conductance of (iii)

K. Keren, Science, 302 (2003) 1380

CNFET SELF-ASSEMBLED USING DNA







ρ = 10^6 transistors / mm^2

0 V to 0.8 V = logic 0

2 V to 5 V = logic 1

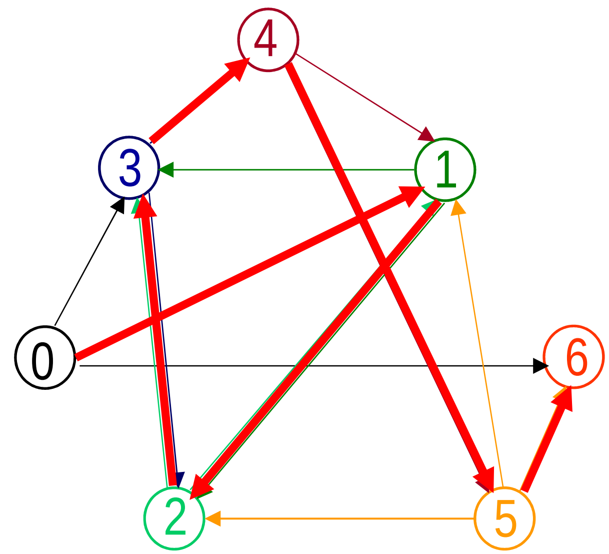
Starting with a circuit description, using tools for placement, routing, and electrical simulation it is possible to develop a viable circuit.

Published online at www.stacks.iop.org/Nano/15/1240

THE POTENTIAL TO PERFORM CALCULATIONS

1994 - Leonard Adleman

Step 1	Generate random paths through the graph;
Step 2	Keep only those paths that begins with 0
and	end with 6;
	The product of *Step 1* was amplified by PCR using primers O_0 and $\bar{O}_6$
Step 3	If the graph has *n* points, then keep only those paths that enter exactly *n* points;
	The product of *Step 2* was submitted to electrophoresis and 140-bp dsDNA was extracted
Step 4	Keep only those paths that enter all of the points of the graph once;
	The product of *Step 3* was purified with $\bar{O}_j$ (0<j<6) biotin-avidin magnetic beads system



O_i	5' - T A T C G G A T C G G T A T A T C C G A - 3'
O_j	G C T A T T C G A G C T T A A A G C T A
O_k	G G C T A G G T A C C A G C A T G C T T
$O_{i\to j}$	G T A T A T C C G A G C T A T T C G A G
$O_{j\to k}$	C T T A A A G C T A G G C T A G G T A C
$\bar{O}_j$	3' - C G A T A A G C T C G A A T T T C G A T - 5'

....$O_{i\to j}$ | $O_{j\to k}$.....

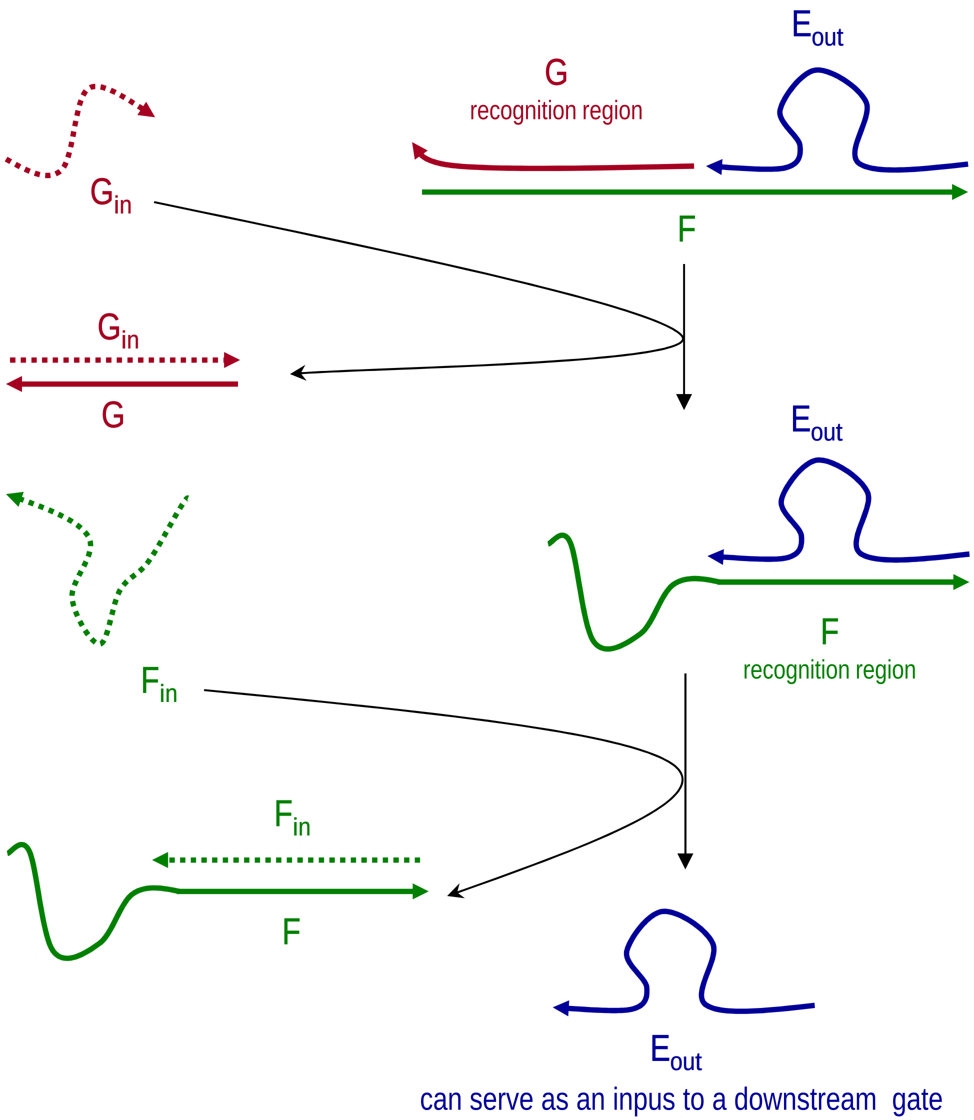
G T A T A T C C G A G C T A T T C G A G C T T A A A G C T A G G C T A G G T A C

C G A T A A G C T C G A A T T T C G A T

$\bar{O}_j$

L.M. Adleman, Science, 266 (1994) 1021

COMPUTATIONAL CIRCUIT LOGIC GATE



AND gate
performs a logical "and" operation on two inputs, A and B

A	B	Q
0	0	0
0	1	0
1	0	0
1	1	1

The idea

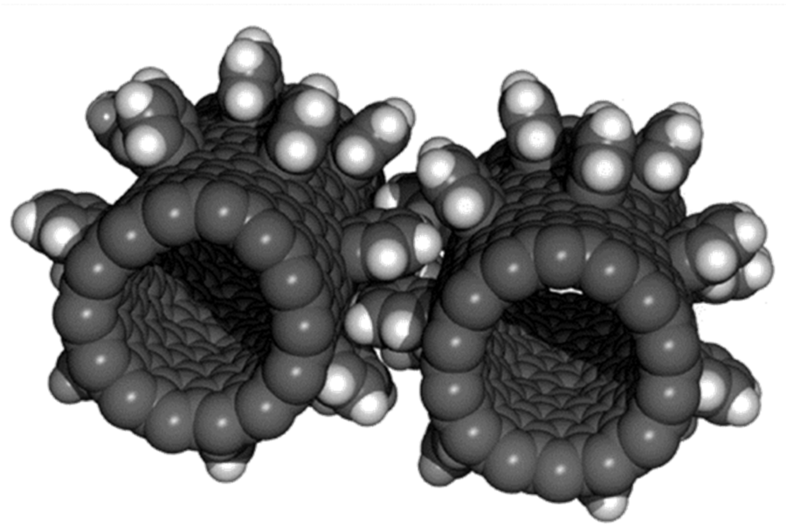
If A and B are both 1, then Q should be 1

	REACTANTS	PRODUCTS
1	EFG, no input	Same as reactants
2	EFG + F_{in}	Same as reactants
3	EFG + G_{in}	EF + GG_{in}
4	EFG + F_{in} + G_{in}	E + FF_{in} + GG_{in}

G. Seeling et al., Science, 314 (2006) 1585

BIOLOGICAL MOLECULES IN NANOELECTRONICS

NANO-GEARS



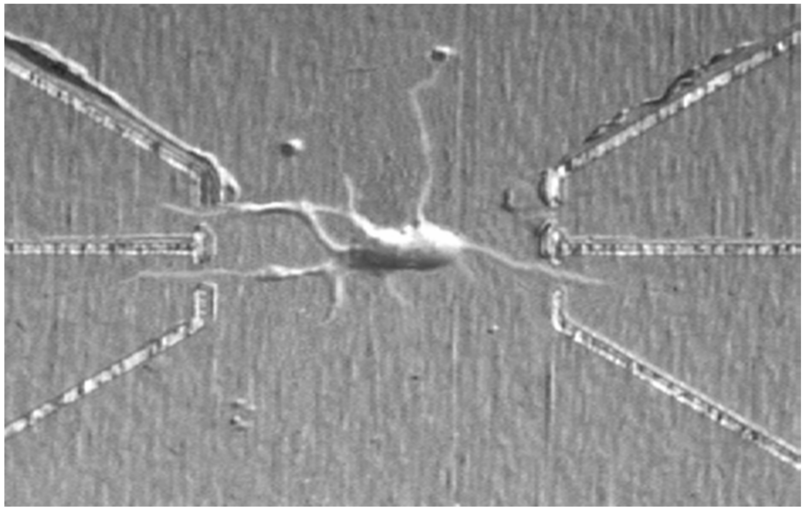
✓attaching benzyne molecules to the outside of a nanotube to form gear teeth.

✓ laser creates an electric field around the nanotube.

✓ placing two opposite charges on different faces of the nanotube, the electric field will drive the nanotube around it.

http://grin.hq.nasa.gov/ABSTRACTS/GPN-2000-001535.html

NEURON INTEGRATED FET



✓Detection, Stimulation, and Inhibition of Neuronal Signals

✓Arrays of nanowire-neuron junctions enable simultaneous measurement of the rate, amplitude, and shape of signals propagating along individual axons and dendrites.

F. Patolsky, et. al., *Science*, 313 (2006) 1100

CONCLUSION

- ✓ demonstrations that may lead to useful application of nanoassembly are appearing;
- ✓ increased level in manipulation and automation are needed to prototype more complex and useful devices;
- ✓ pick-and-place operations and the construction of 3-D nanostructures are primitive and need further development;
- ✓ there is a need in creating programmed self-assembling rather than nanomanipulation