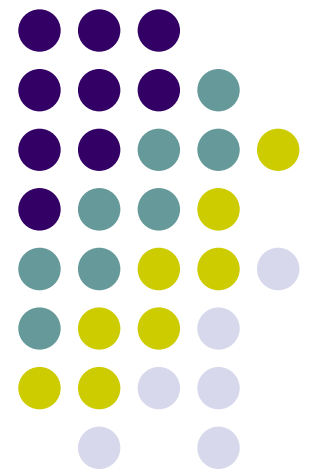


CS257 Introduction to Nanocomputing

Overview of Crossbar-Based
Computing

John E Savage

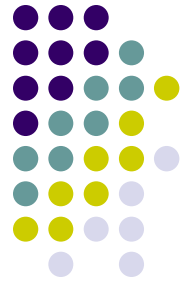




Overview

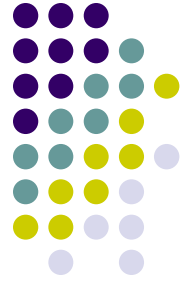
- Intro to NW growth methods
 - Chemical vapor deposition and fluidic assembly
 - Nano imprinting
 - Nano stamping
- Four crossbar addressing methods
 - Overview of nature of analytical results

The End of Photolithography



- [2001 ITRS \(Roadmap\)](#) predicts within 10-15 years “most known technological capabilities will approach or have reached their limits.”
- Nanotechnology will replace photolithography

What are Nanotechnologies?



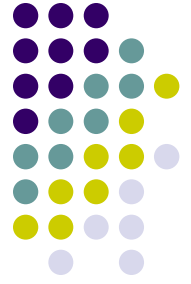
- Their smallest dimension is measured in nanometers – about 10x the diameter of a hydrogen molecule.
- They are too small to be seen with a light microscope
- Assembly involves randomness
- They are used to create new materials, including those that “compute.”

Sources of Information on Nanotechnology

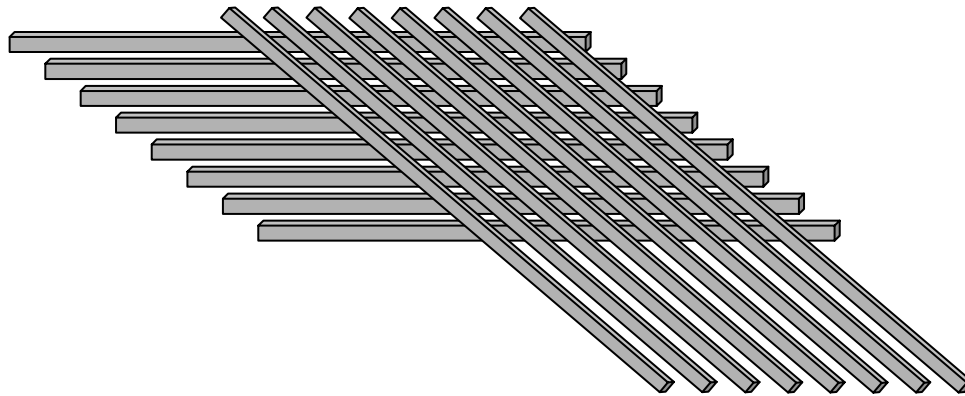


- The [Wikipedia](#) nanotechnology site has lots of useful info but shortchanges the work on crossbars.
- The NASA [web site](#) has nice photos and videos highlighting NASA's interests.
- The Lieber Research Group [web site](#) has a demo of the development of a nanocomputer.

Characteristics of Computational Nano Devices



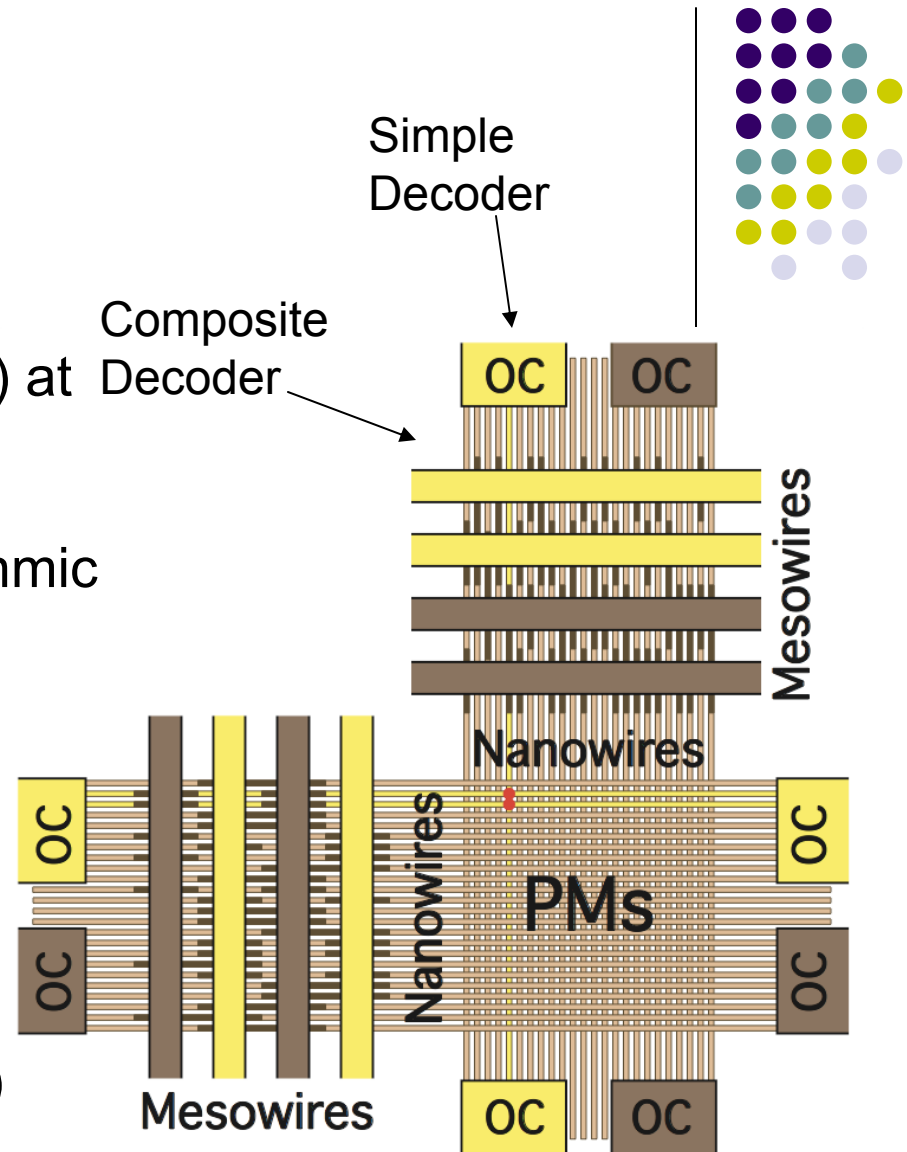
- Nano devices are going to be regular
 - Crossbars are a promising structure



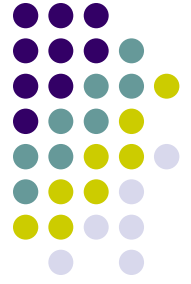
- DNA, which is programmable, may be used to produce templates for wires, gates.

The Crossbar

- Programmable molecules (PMs) at NW crosspoints.
- NWs form contacts groups at ohmic contacts (OCs).
- NW/MW junctions form FETs.
- NWs controlled by mesoscale wires (MWs).
- Dense memories (10^{11} bits/cm²) and circuits predicted.

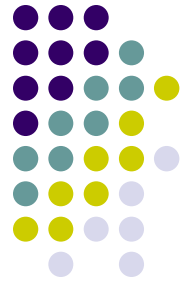


Characteristics of Computational Nano Devices



- Each device is different
 - Must **discover** device characteristics and
 - **Configure** it to provide required functionality.
- When assembling different nano-objects, their locations can't be controlled.
- Learning to live with randomness and faults is essential.

Understanding Crossbar Architectures



- Contact with nano-devices will be via **big** meso-scale wires (MWs).
- Nanowire crossbars will achieve high density **if** each NW is not connected to a distinct MW
- We need addressing schemes that “turn on” one NW in each dimension with **few** MWs.



Nanowires and Nanotubes

- Carbon nanotubes (CNTs)
 - Are being used in regular 2D arrays (Nantero)
- Semiconducting nanowires (NWs)
 - Grown individually and assembled fluidically or
 - Grown in groups and stamped on chips

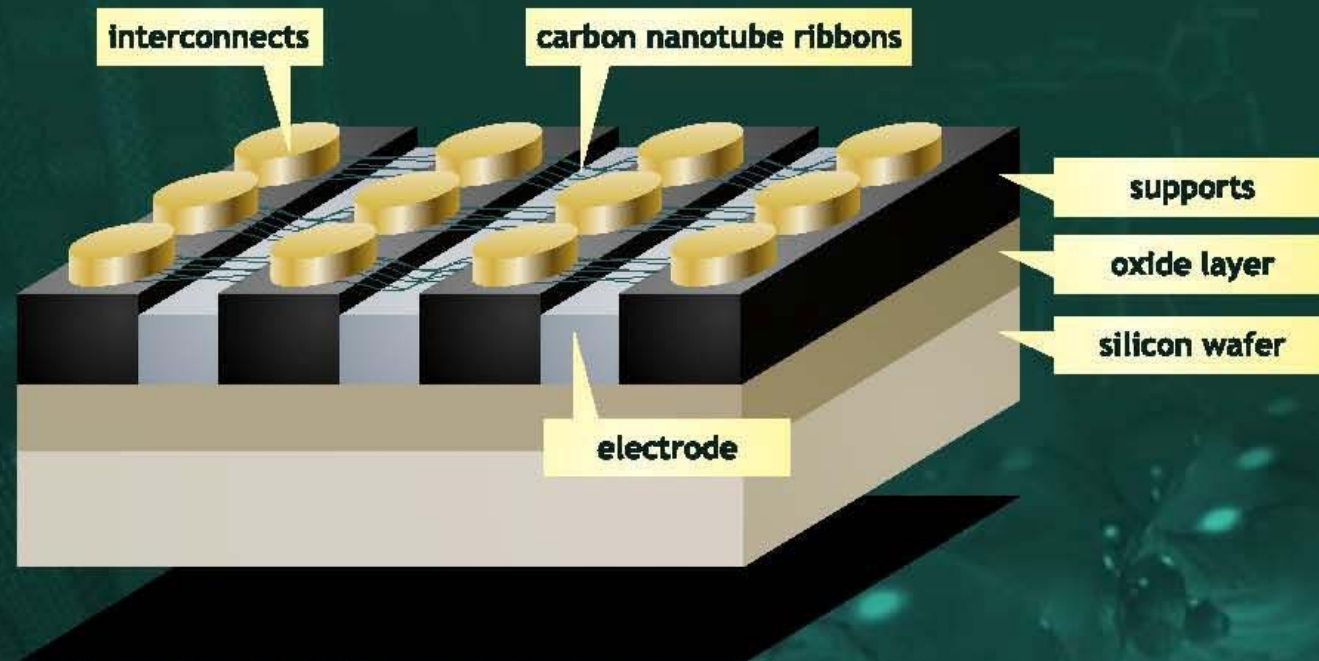


NANTERO

The principles of operation of NRAM™

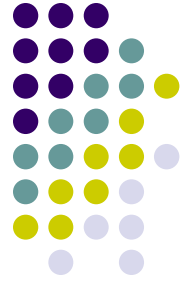
The principles of operation of NRAM™ | The benefits of NRAM™ | Applications

Structure of a memory cell



NRAM – Nonvolatile RAM

Crossbars of Carbon Nanotubes



- Electrostatic attraction used to make contacts, repulsion breaks them.
- Nantero's claims:
 - Permanently nonvolatile memory
 - Speed comparable to DRAM/SRAM
 - Density comparable to DRAM
 - Unlimited lifetime
 - Immune to soft errors
- Now on the LSI production line.



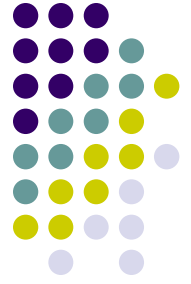
Molecular Data Storage

- Goal: molecular switches at crosspoints.
- Switching medium: supramolecular layer
 - Electric field across NW junctions switches state of molecule between conducting and non-conducting.
 - Switching due to
 - a) change of molecule shape, or
 - b) growth of metal filaments, or something else.



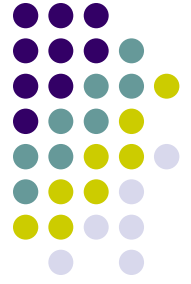
Types of Nanowire

- Encoded NWs
 - Batches of NWs with different encodings grown in advance
 - NWs drawn at random from mixture of NW types and assembled fluidically
- Uniform NWs
 - Many identical NWs grown in advance
 - NWs stamped or imprinted on chip
 - NWs differentiated after assembly

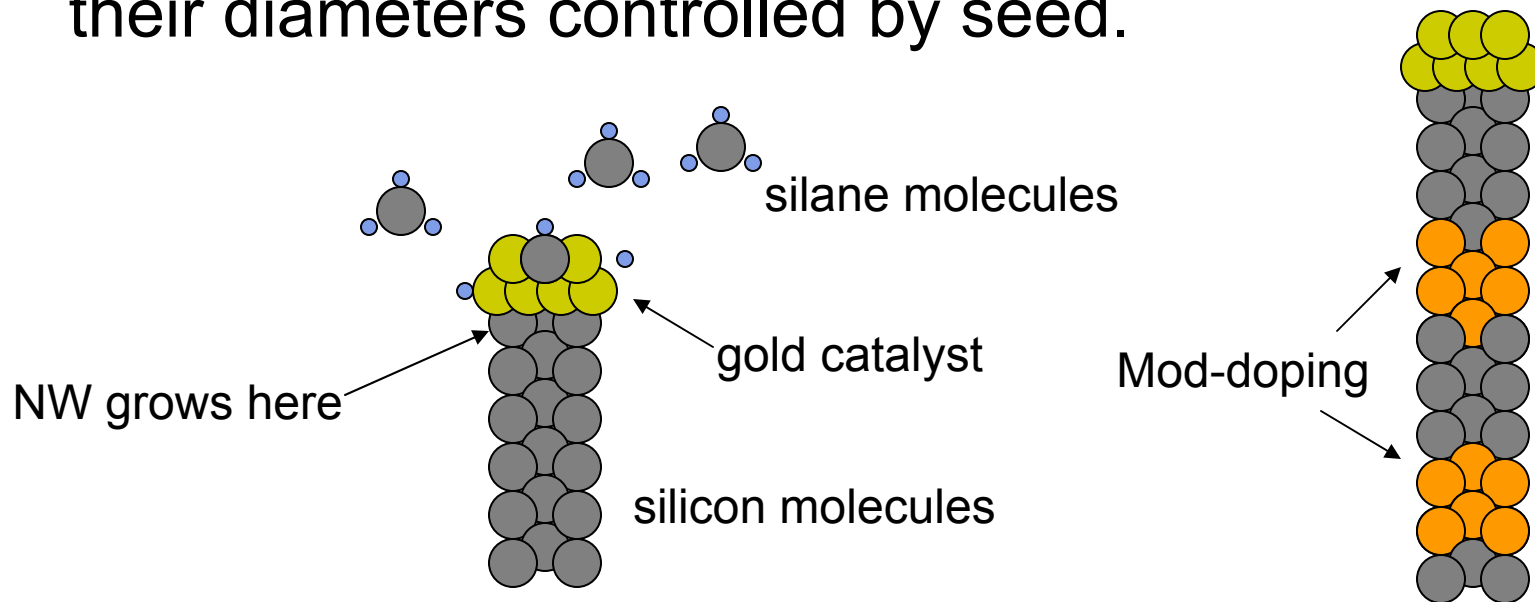


Encoded NWs

Nanowires Grown/Encoded by Chemical Vapor Deposition

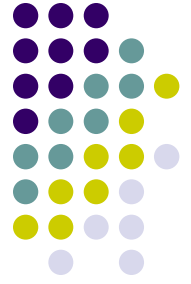


- Semiconducting NWs grown from seed catalysts; their diameters controlled by seed.

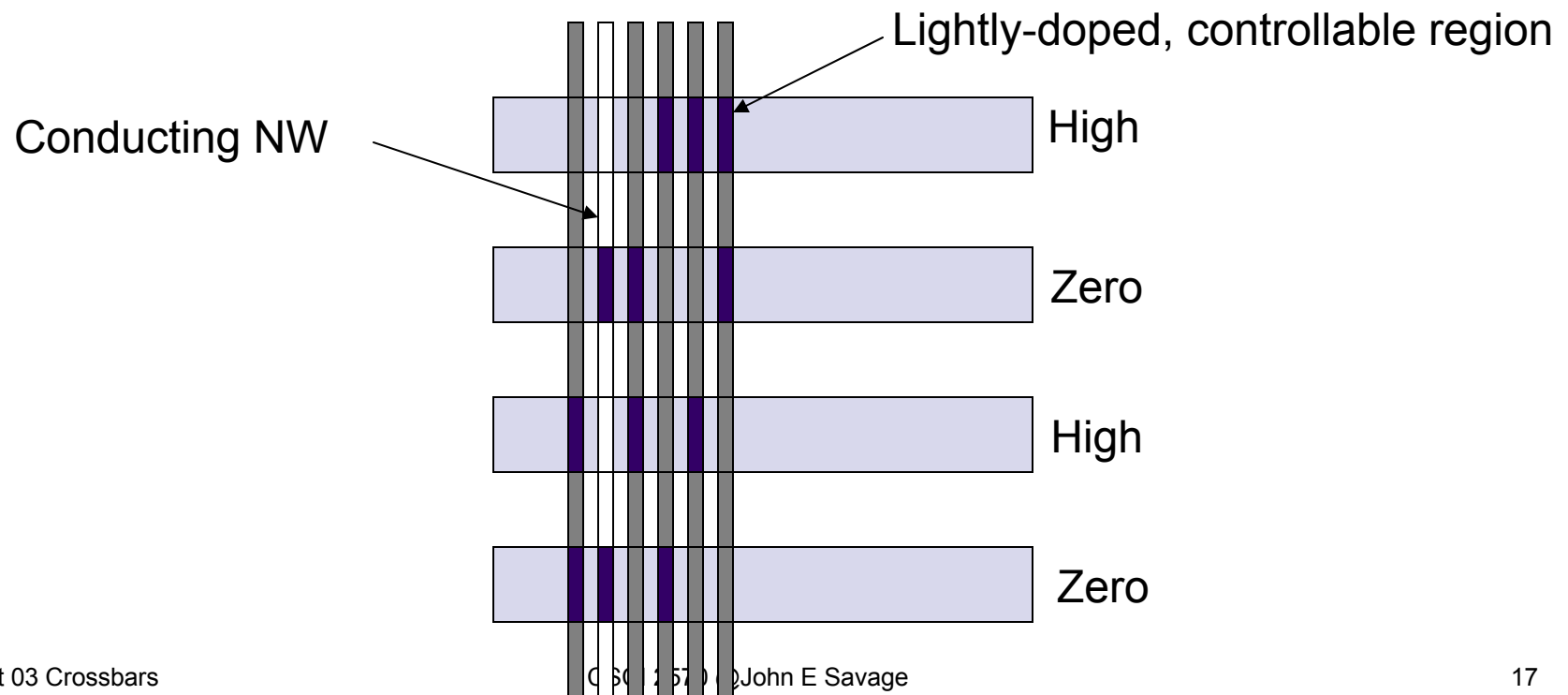


- **Modulation Doping:** dopants added to gas as NWs grow; doped sections have lithographic length.

Addressing Modulation-Doped Nanowires



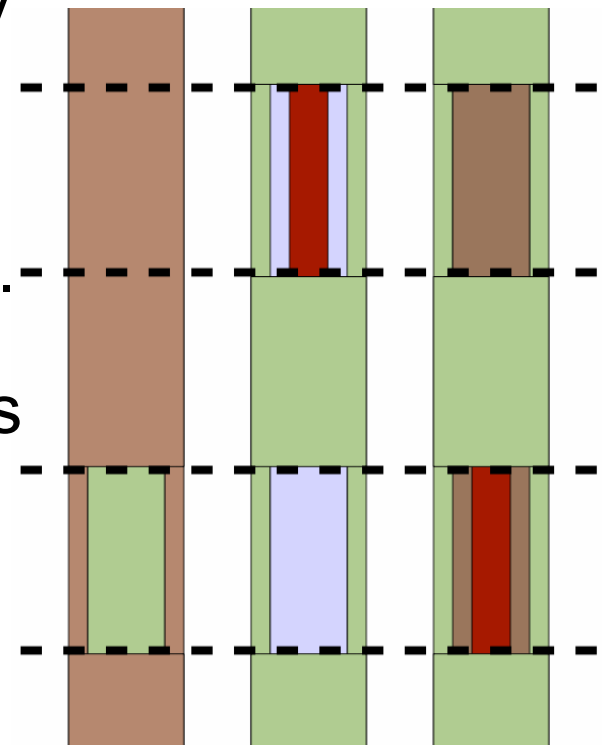
- A meso-scale wire (MW) and lightly-doped NW region form field effect transistor (FET).



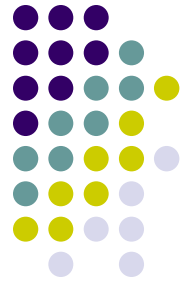


A Decoder for Core-Shell NWs

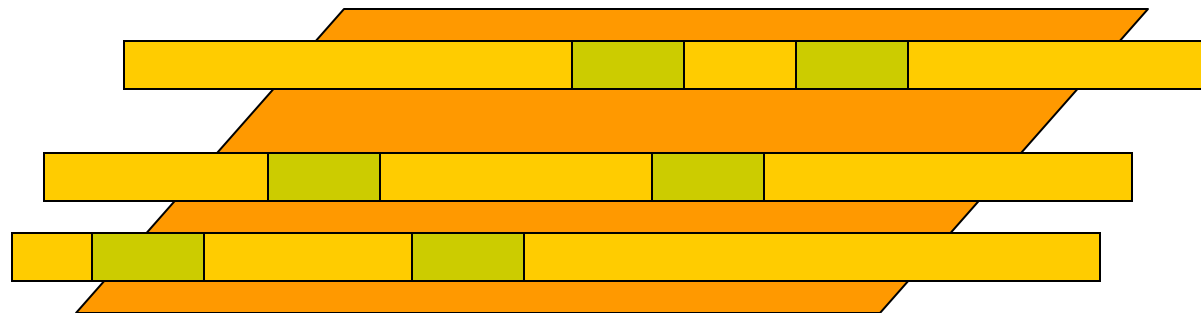
- NWs have s shells of m differentially etchable materials; materials in adjacent shells are different.
- They form $N = m(m-1)^{(s-1)}$ NW types.
- Under each MW etch the s materials forming a NW shell sequence.
- N NWs are controlled by N MWs.
- 12 codewords (and MWs) suffice to control 1,000 NWs for $w = 10$!



Fluidic Assembly of Encoded Nanowires



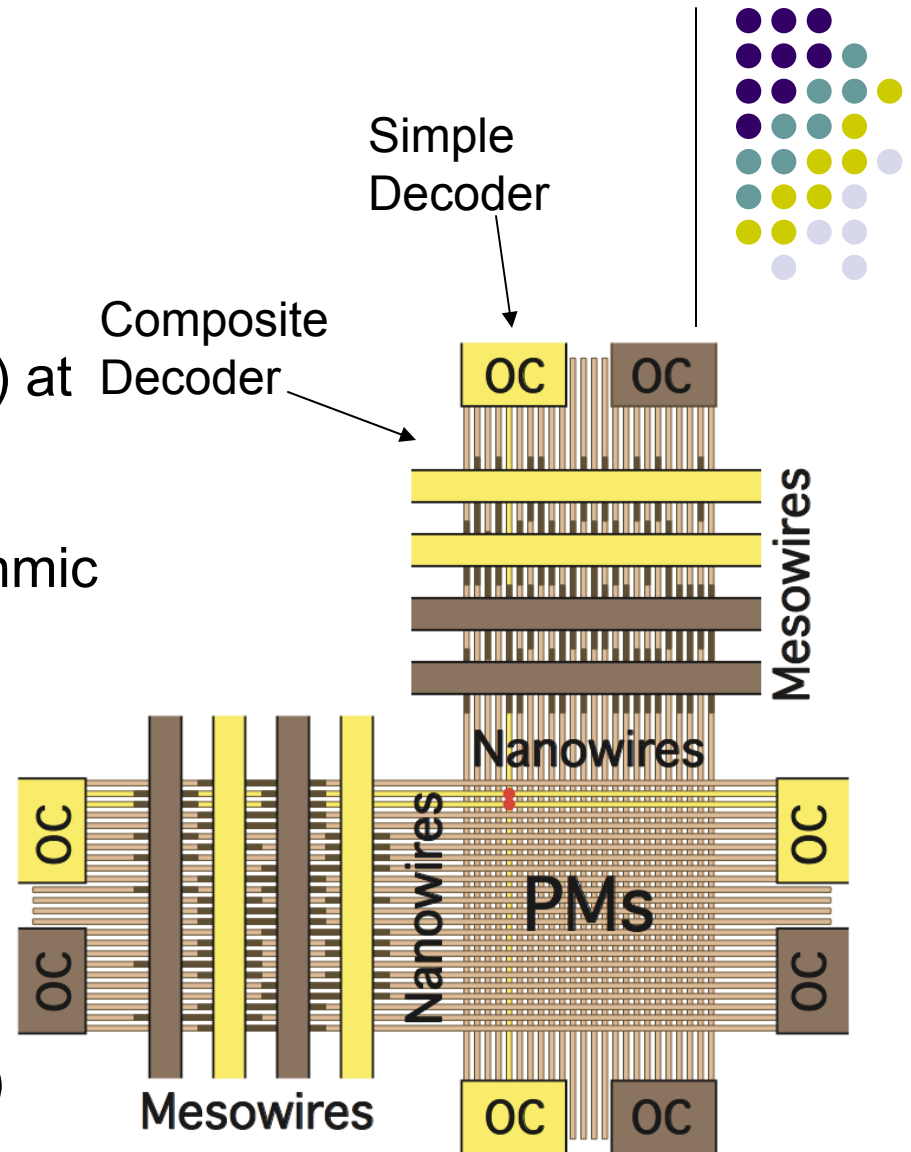
- Random sample of coded NWs is floated on a liquid, deposited on chip, and dried.



- NWs self-assemble into parallel locations.
- Process repeated at right angles – crossbar.

The Crossbar

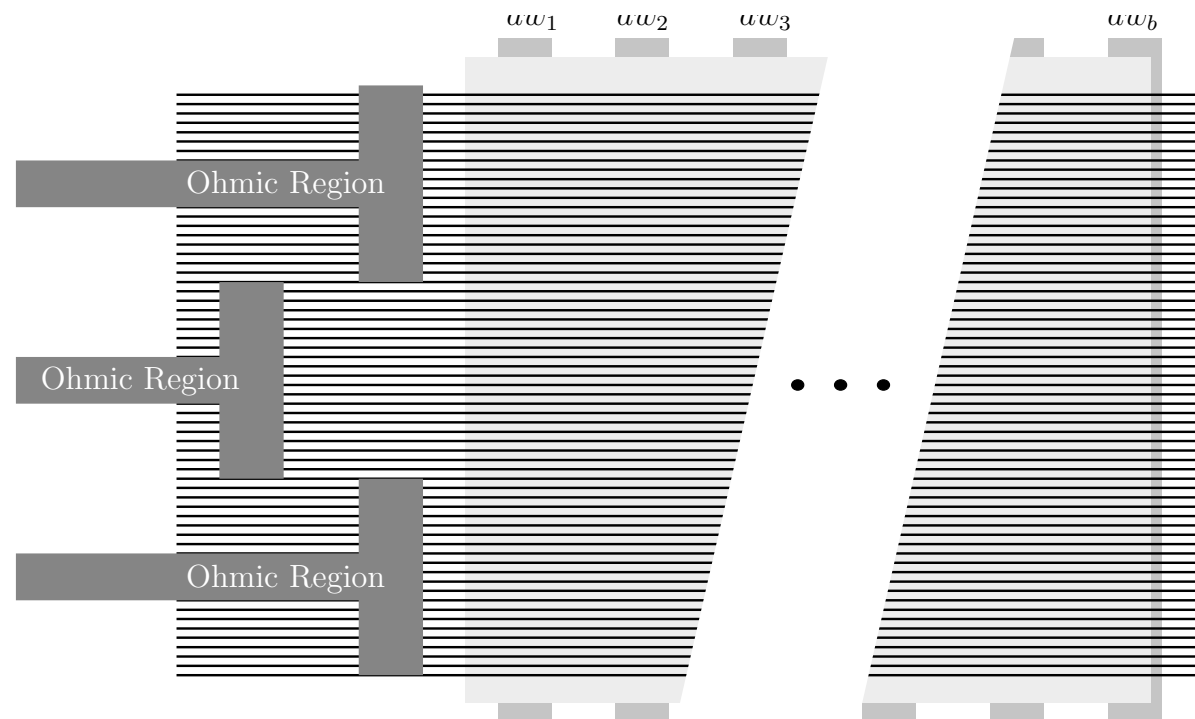
- Programmable molecules (PMs) at NW crosspoints.
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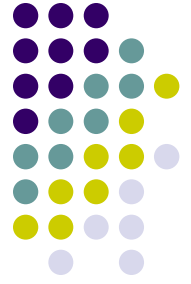


Multiple Simple Decoders

- They reduce the number of NW types needed.

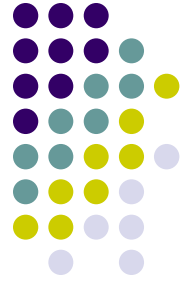


Sensitivity to Fluidic Assembly

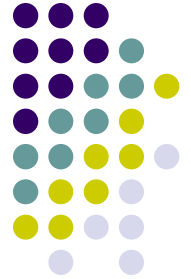


- Modulation-doped NWs **are** sensitive to their length-wise displacement.
- Core-shell NWs **are not** sensitive to their length-wise displacement.

How Many Addressable NWs in Each Crossbar Dimension?

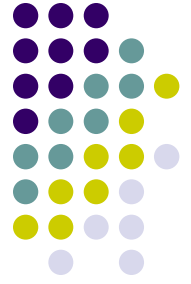


- Depends on number of distinct NWs/simple decoder
 - Should all NWs in each region be distinct?
 - Shall we aim for at least half distinct?
 - Or shall we take what we get?
- If we have N NWs in each dimension, what is probability there $0.75 N$ different NW addresses?
- Experiment and theory say that 10-15 different NW types give $0.75 N$ different addresses with probability 0.99!

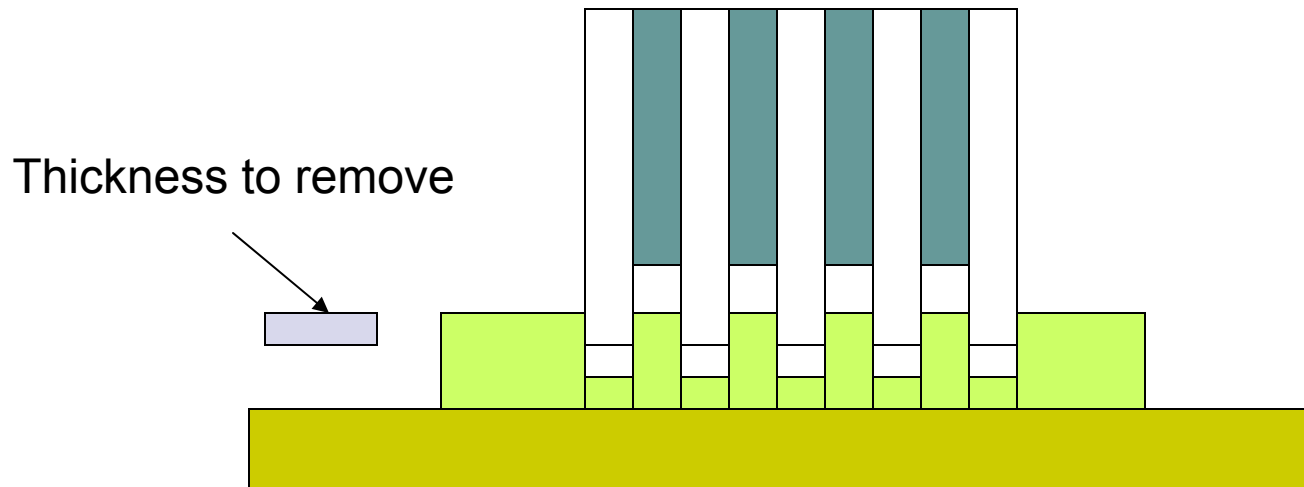


Uniform Nanowires

Metallic NWs Grown by Nanoimprinting



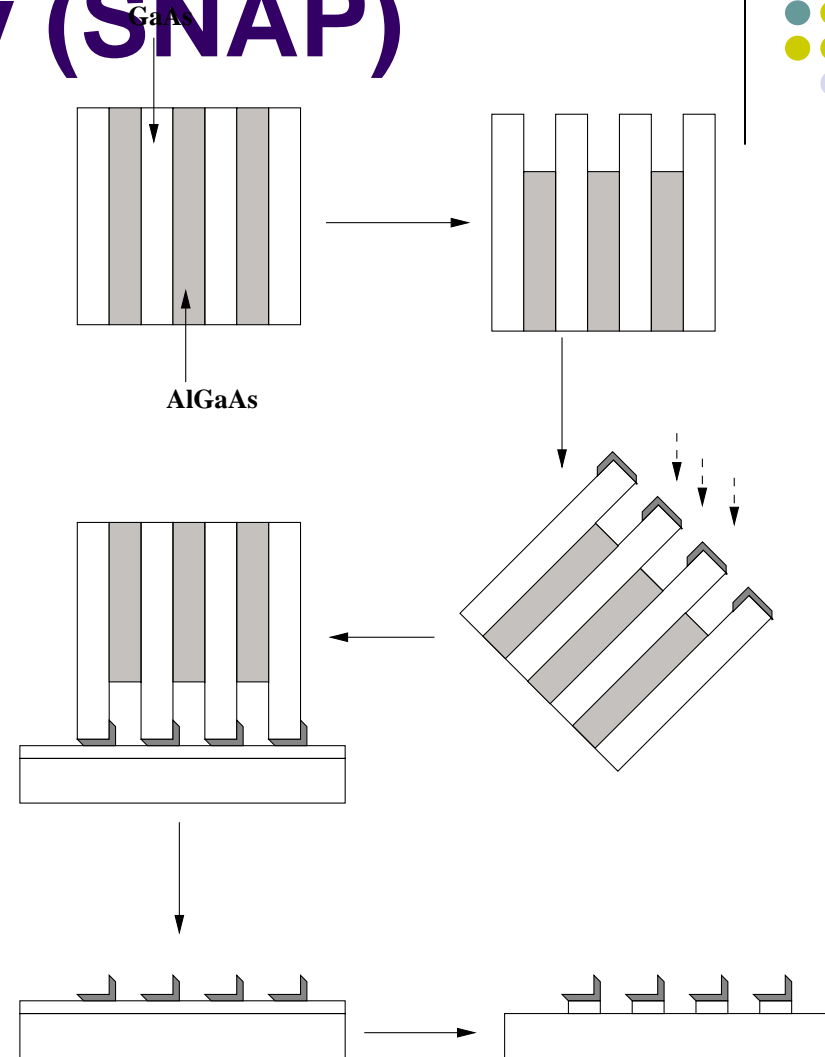
- Etch AlGaAs in an MBE block, sawtooth pattern impressed on soft polymer.
- Remove thin layer of polymer
- Deposit NWs in gaps per lithography



Si NWs Grown via Nanolithography (SNAP)



- MBE creates block
- AlGaAs etched
- Metal deposited
- Transfer to sticky surface
- Surface has Si SiO₂ on Si substrate
- Etch Si, remove metal giving Si NWs on SiO₂

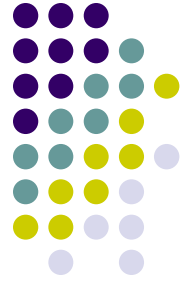


Addressing NWs with Lithographic Wires

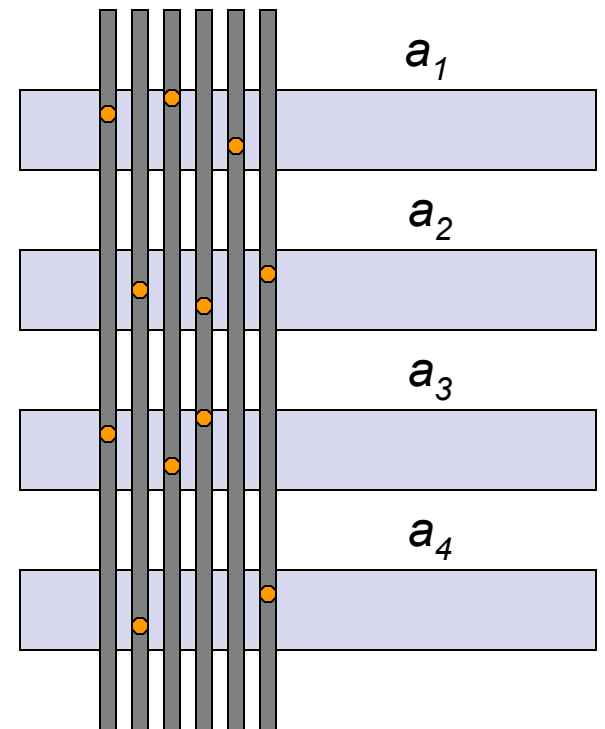


- NWs are all the same
- How can one NW in each dimension be activated?
- Two methods:
 - Randomized contact decoder
 - Randomized mask-based decoder

Randomized-Contact Decoder



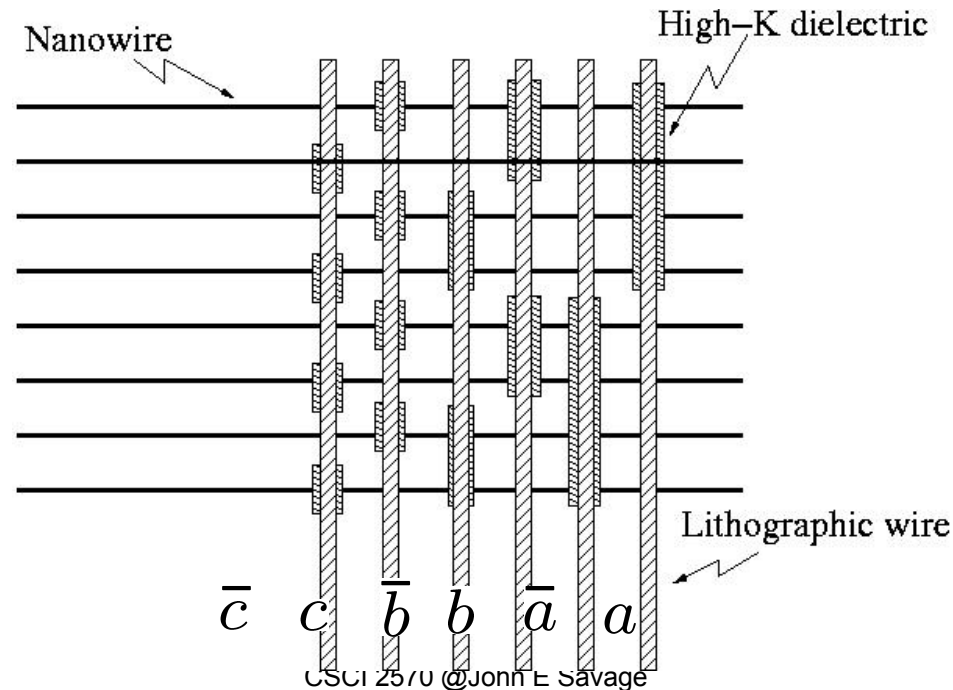
- Gold particles are scattered at random. Probability $p \approx 0.5$ a particle between NW/MW pair.
- Particle(s) between a MW and a NW forms a FET.
- Each NW given a “code.”



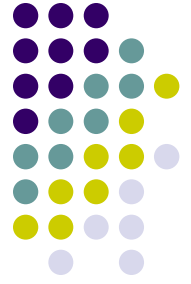
Mask-Based Decoder Using High-K Dielectric Regions



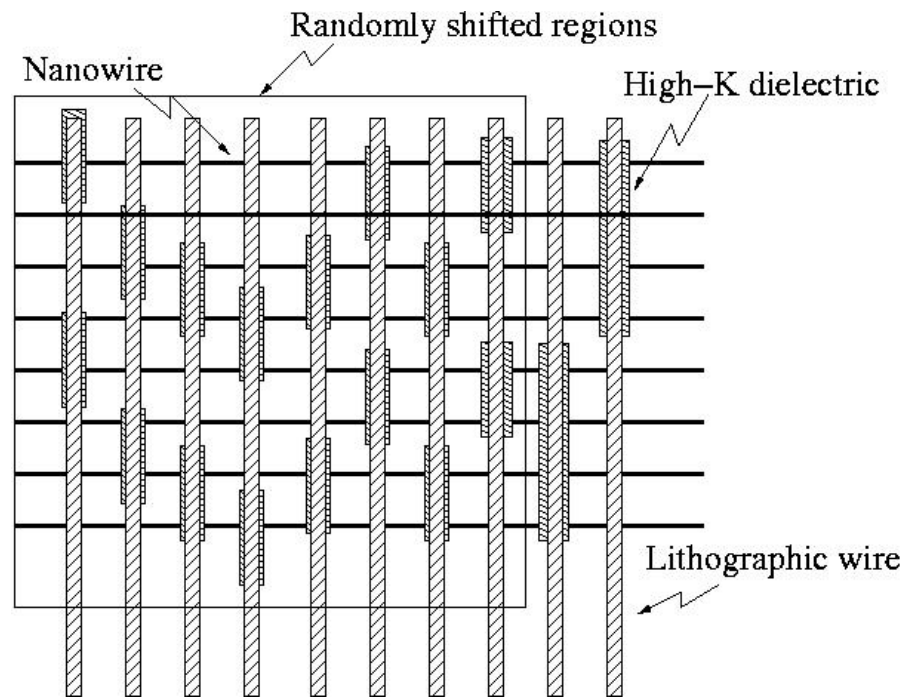
- A high-K dielectric couples doped NW & MW
 - Each NW given a code.
 - **Problem:** Can't manufacture NW-sized regions.



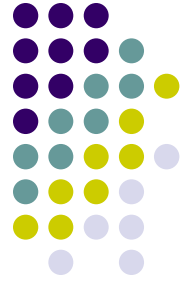
Randomized Mask-Based Decoder



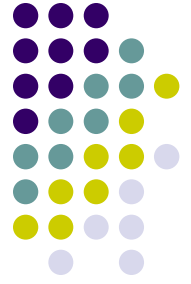
- Randomly shift smallest dielectric regions.
- Regions stamped or defined lithographically



Conclusions Concerning Randomized Decoders



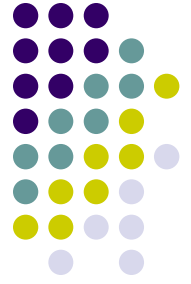
- Mask-based decoder requires
 $M \cong 200$ MWs when $\varepsilon = .01$, yield 10^3 NWs
- Randomized-contact decoder requires
 $M \cong 10$ MWs when $\varepsilon = .01$, yield 10^3 NWs



Codeword Discovery

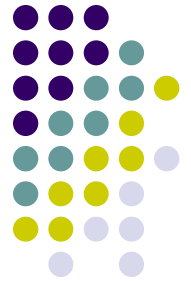
- Codewords assigned randomly to NWs by assembly process
- Algorithms must be employed to discover which codewords assigned to NWs.
- Address translation circuit required to map external addresses to internal ones.

Role of Design and Analysis



- Evaluation of addressing strategies (probabilistically)
- Helps designer to
 - choose parameter values,
 - identify limitations on designs, and
 - introduce new designs.
- Evaluate codeword discovery algorithms
- Evaluate fault avoidance/correction strategies

Conclusions About Crossbars



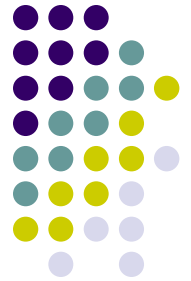
- A promising nanotechnology
- Its assembly is essentially stochastic
- Analysis is important in understanding nanotechnology-based systems.
 - Surprising conclusions sometimes follow.

Other Applications of Nanotechnologies

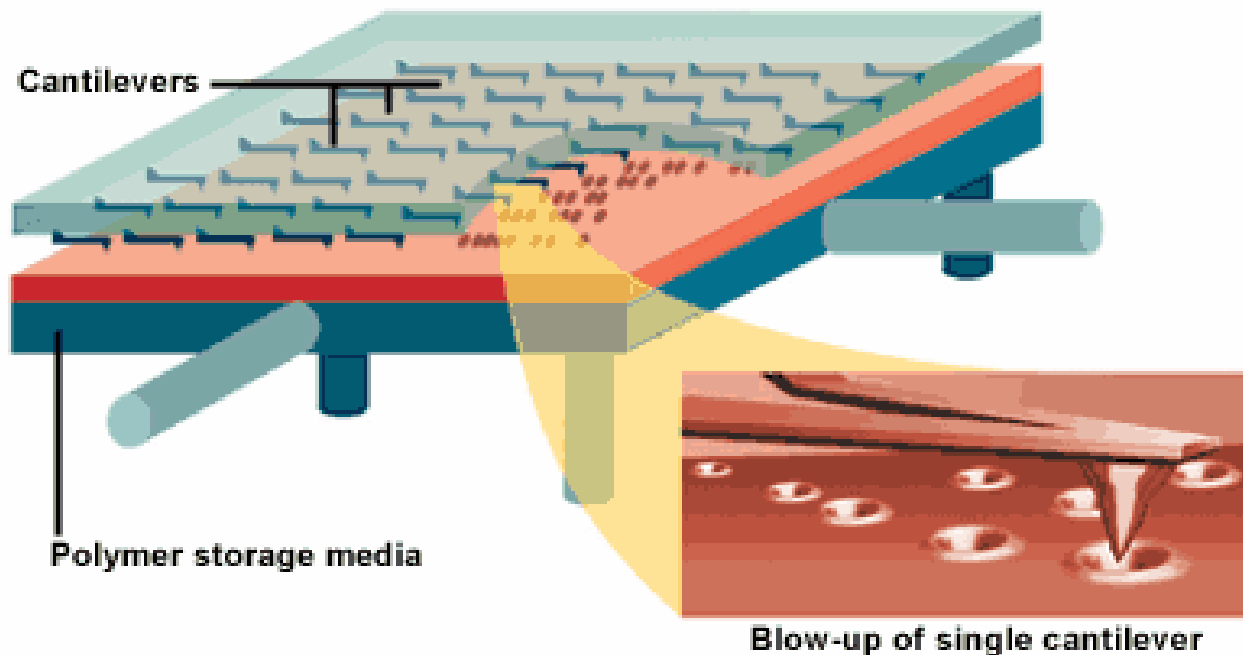


- Millipede – array of AFMs
 - See readings
- CMOL
 - Hybrid nano/CMOS circuits
- Micro to Nano Addressing Block (MNAB)
 - Field effect used to control NWs

The “Millipede” – Atomic Force Microscope Memory



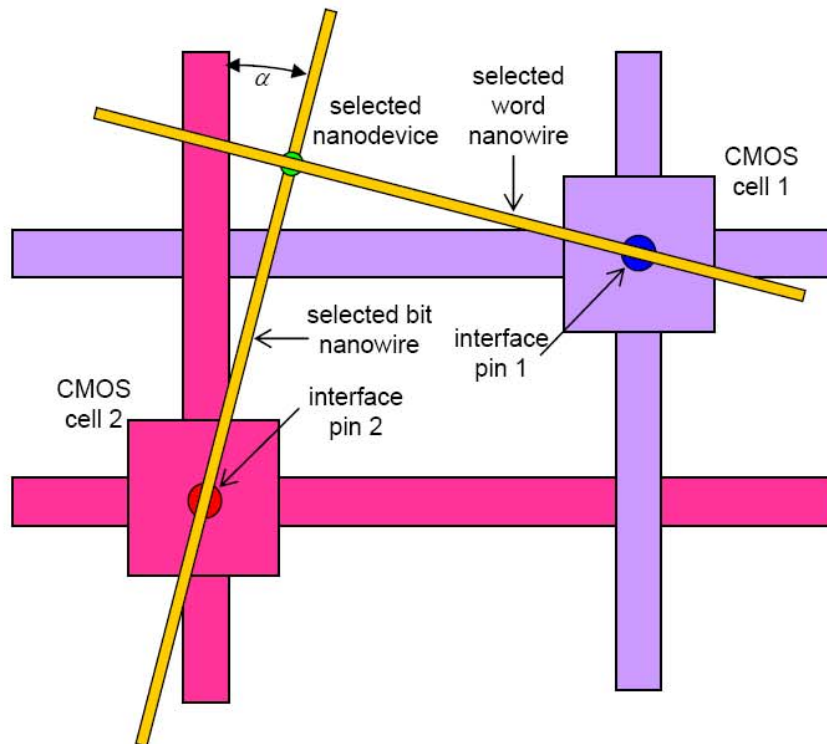
BUMPY STORAGE



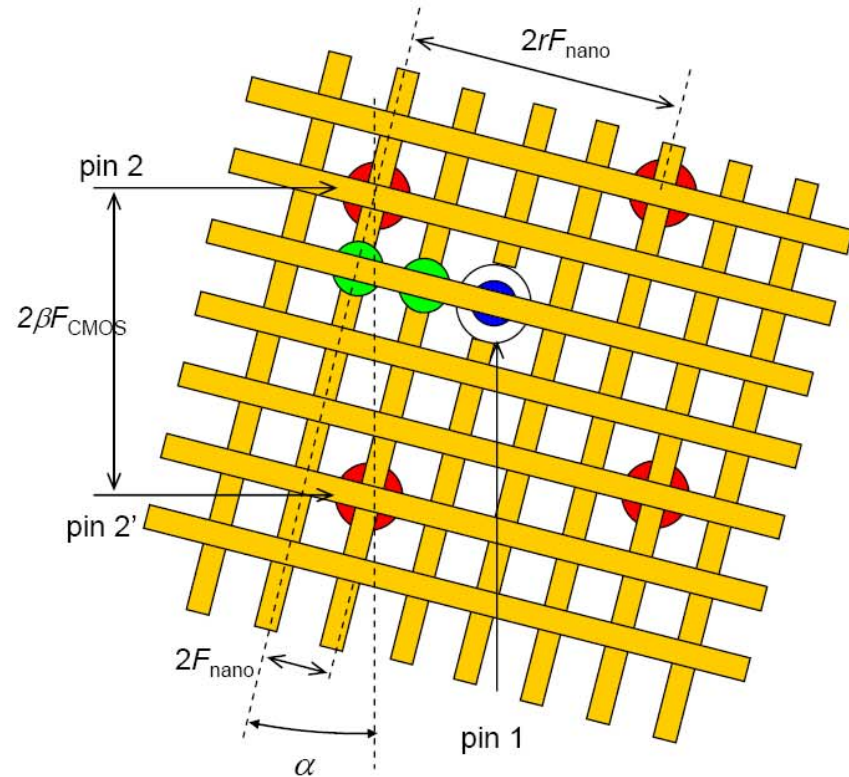
IBM's "millipede" stores bits by making nanoscale indents in a polymer using 1,024 tiny tips, attached to cantilevers. Heating the polymer "erases" the data by rearranging the molecules in the polymer so that the material is smooth again.

CMOL CONCEPT (II)

Most important: tilt $\alpha = \sin^{-1}(F_{\text{nano}}/\beta F_{\text{CMOS}})$



Nanodevice addressed
via two CMOS cells



Every nanodevice
may be addressed!

Portland, September 2005

13

MNAB

