CSCI 2570 Introduction to Nanocomputing

Errors in Crossbars

John E Savage

Lecture Outline

- General Properties of nanoarrays
- NanoFabrics – an early model for nanoarrays
- NanoPLAS – A programmable architecture
- Coping with defects

Technology Forecast

- DeHon (JETC, Vol. 1, No. 2, 2005) predicts one to two orders magnitude greater density with nanoarrays than FPGAs realized in 22*nm* lithography, even if latter components are defect-free!

NW Properties

- Axially doped NWs
  - Resistance: 0.1MΩ (on) to 10GΩ (off) (>10^4 ratio)
- Radially doped NWs
  - Use as shield and control spacing or to encode NW.
- Silicide – coating Si with Ni and annealing forms metallic NiSi
  - Resistivity of NiSi = 10^{-5} Ωcm, of Si = 10^{-3} Ωcm
  - This reduces NW contact resistance to 10KΩ

Demonstration Project

- Chen et al. [2003]:
- Ti/Pt-[2] rotaxane-Ti/Pt sandwich exhibiting state storage with resistance change by > x10
  - From 500KΩ to 9MΩ for $1600nm^2$ jnctn
- State switched with +/- 2V, read at +/- 0.2V
- Molecular sandwich created with Langmuir-Blodgett
- 8 x 8 crossbar constructed

Area/Length Comparisons

- SRAM-based programmable crosspoint has area 2,500λ^2 versus 25λ^2 for NW crossing [DeHon 1996].

- NWs can be grown to hundreds of microns in length, but only for large NWs.
  - 10μm x 10μm arrays have been demonstrated

Defects in Wires and Crosspoints

- NWs may break during assembly
  - Diameter can be ≈100 atoms
- Statistical nature of contacts
  - NW-to-MW junctions: small no. of atomic bonds
    - E.g. [Huang 2001]: 95% of contacts good
  - NW-to-NW junctions: composed of 10s of atoms
    - E.g. [Chen 2003]: 85% of crosspoints useable
- Statistical nature of doping
  - Number of dopants per NW diameter is small

Defect Models

- NW Defects
  - Functional: Good contacts at each end, resistance within range, no shorts to other NWs
  - Defective NWs can be found through testing
  - Shells on axial or radial NWs prevent shorts between NWs

- Crosspoint Defects
  - Programmable (Most common state)
    - Resistance can switched between design limits
  - Non-programmable (More common than shorts)
    - Cannot be turned on – too few molecules at junction
  - Shorted into the on state (treat as defective wires)
    - Cannot be programmed into the off state

Experimental Demonstrations of Crosspoint Arrays

- [Chen 2003] 8 × 8 crossbar within a 1 μm^2 area, density of 6.4 Gbits cm^{-2}. Two 4 × 4 crossbar subarrays configured to be a nanoscale demultiplexer and multiplexer that were used to read memory bits in a third subarray. Nanoimprint litho used for NWs
- [Wu 2005] 34 x34 crossbar memory circuits at 30-nm half-pitch nanoimprint lithography used for NWs, LB for film deposition. Read, write, erase and cross-talk were also investigated. Also see [Jung 2004]

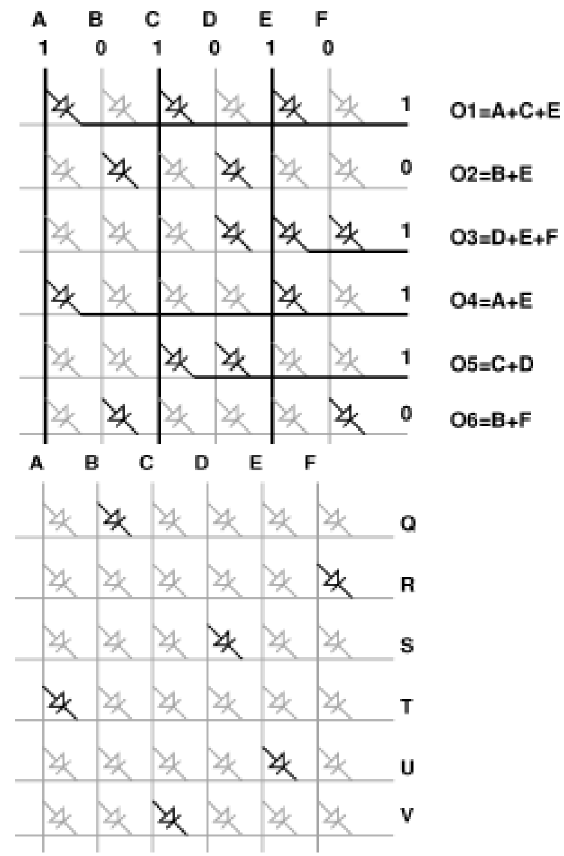
Experimental Demonstrations of Crosspoint Arrays

- Heath and Stoddart have implemented a 400x400 array of NWs with density of 10^{11} bits/centimeter.
  - "Modern DRAM circuits have 140nm pitch wires and a memory cell size of 0.0408 mm^2."
  - "Here we describe a 160,000-bit molecular electronic memory circuit, fabricated at a density of 10^{11} bits cm^{-2} (pitch 33 nm; memory cell size 0.0011 mm^2), that is, roughly analogous to the dimensions of a DRAM circuit projected to be available by 2020."

Programmable Wire-OR Plane

- NWs in black are drawn high by applied voltages
- Output functions shown

- Programmed crosspoints realize a routing network



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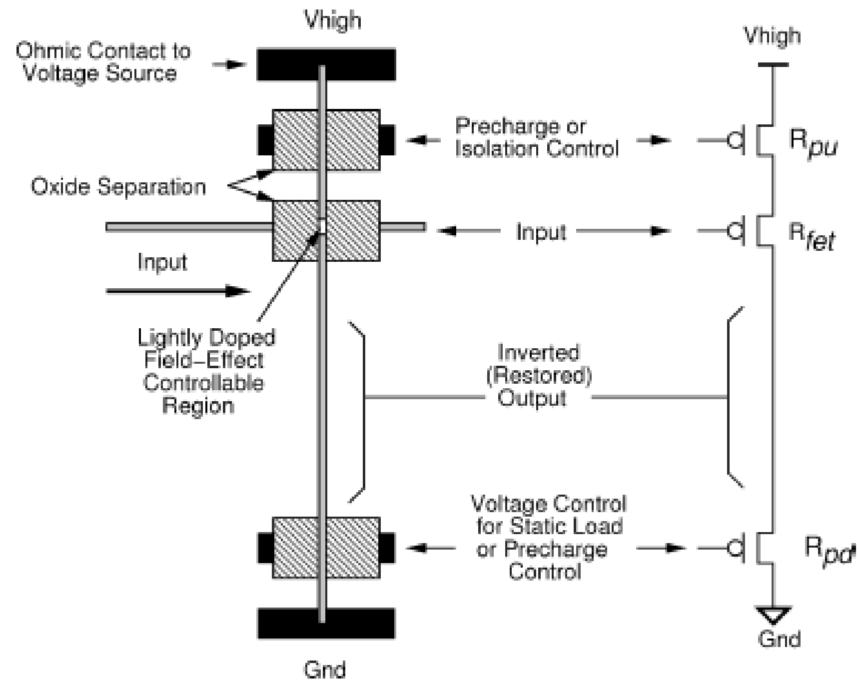
NW Encoding and Decoding

- Goal: turn on one NW in each array dimension
- Earlier lectures describe
  - Undifferentiated NW decoders
    - Random contact decoder
    - Randomized mask-based decoder
  - Differentiated NW decoders
    - Axially encoded NWs
    - Radially encoded NWs

Signal Restoration and Inversion

- Wire-OR non-restoring
  - OR is not universal
- Capacitive coupling of input NW to vertical NW
- FET at intersection
- Gives voltage divider
- Inverter shown at right
- Reverse V_{high} and Gnd to obtain buffer

$$V_{out} = V_{high}\left(\frac{R_{pd}}{R_{pd}+R_{fet}(Input)+R_{pu}}\right)$$



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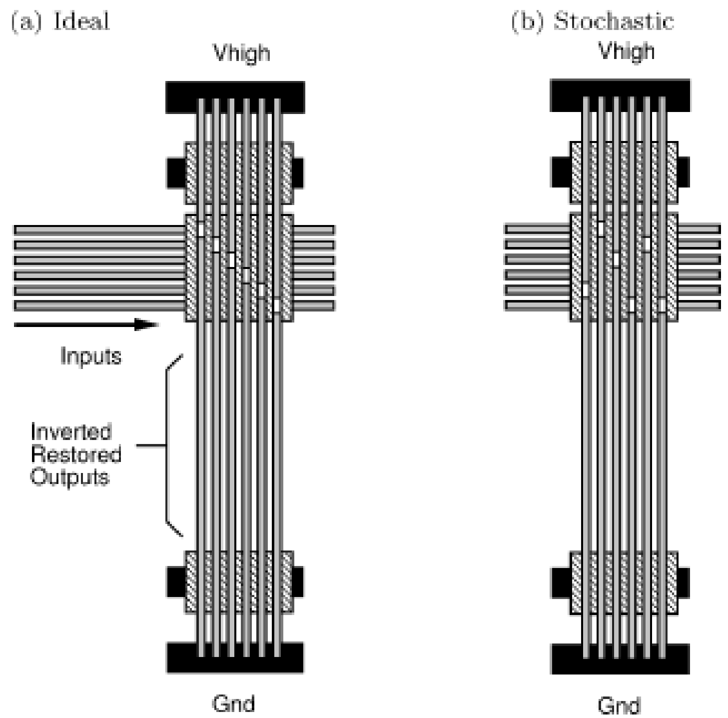
Ideal and Stochastic Restoration Arrays

- Ideal restoration array has one FET/NW
- Stochastic assembly raises its ugly head
  - Some NWs may form FETs with multiple vertical NWs
- How many vertical NWs are needed?
  - A coupon collector problem



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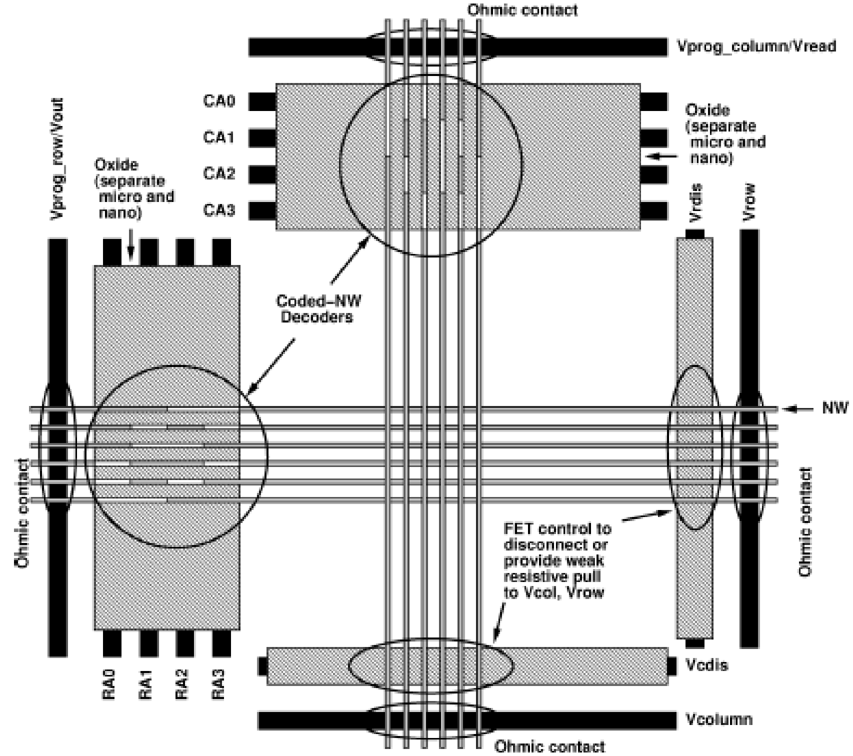
Memory Organization

- Write
  - Apply voltage across junction
- Read
  - Disconnect one end of each NW
  - Drive current from a NW in one dimension to NW in other



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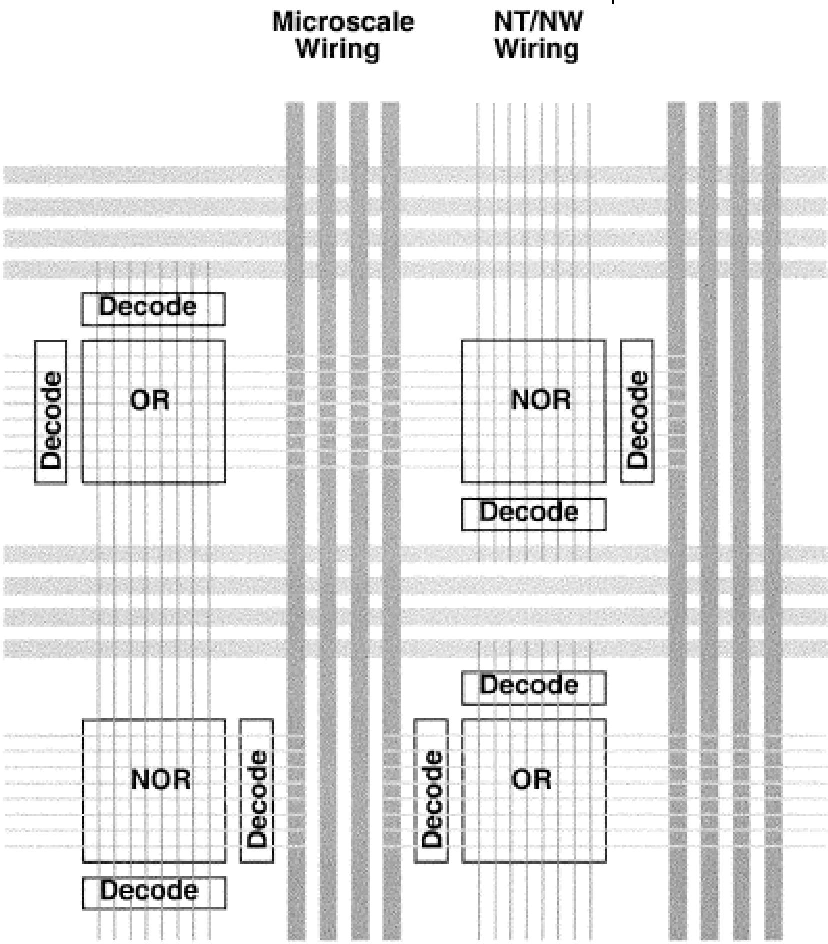
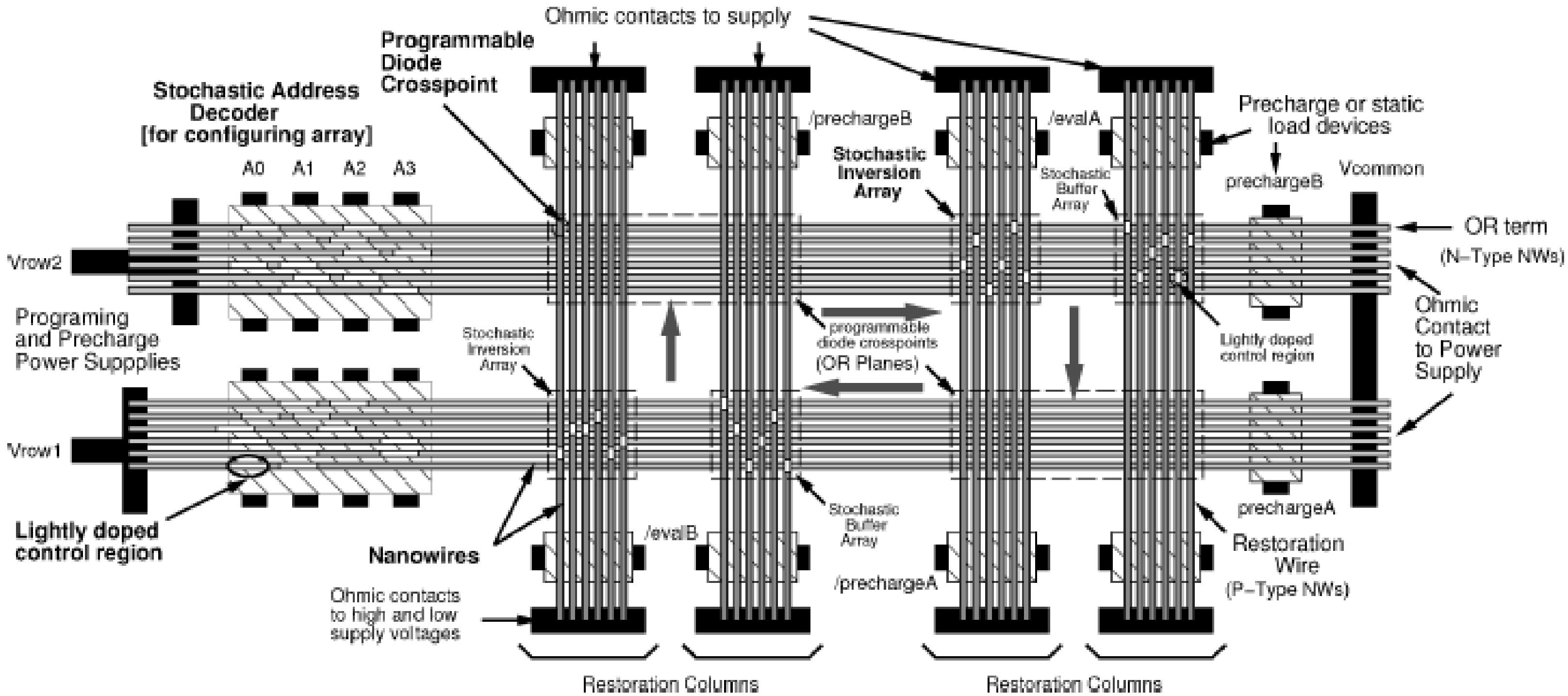
Array-Based Architectures

- Crossbars can be used for storage, computation or routing
- Amenable to sparing and remapping
- Challenge:
  - Defect tolerance and avoidance

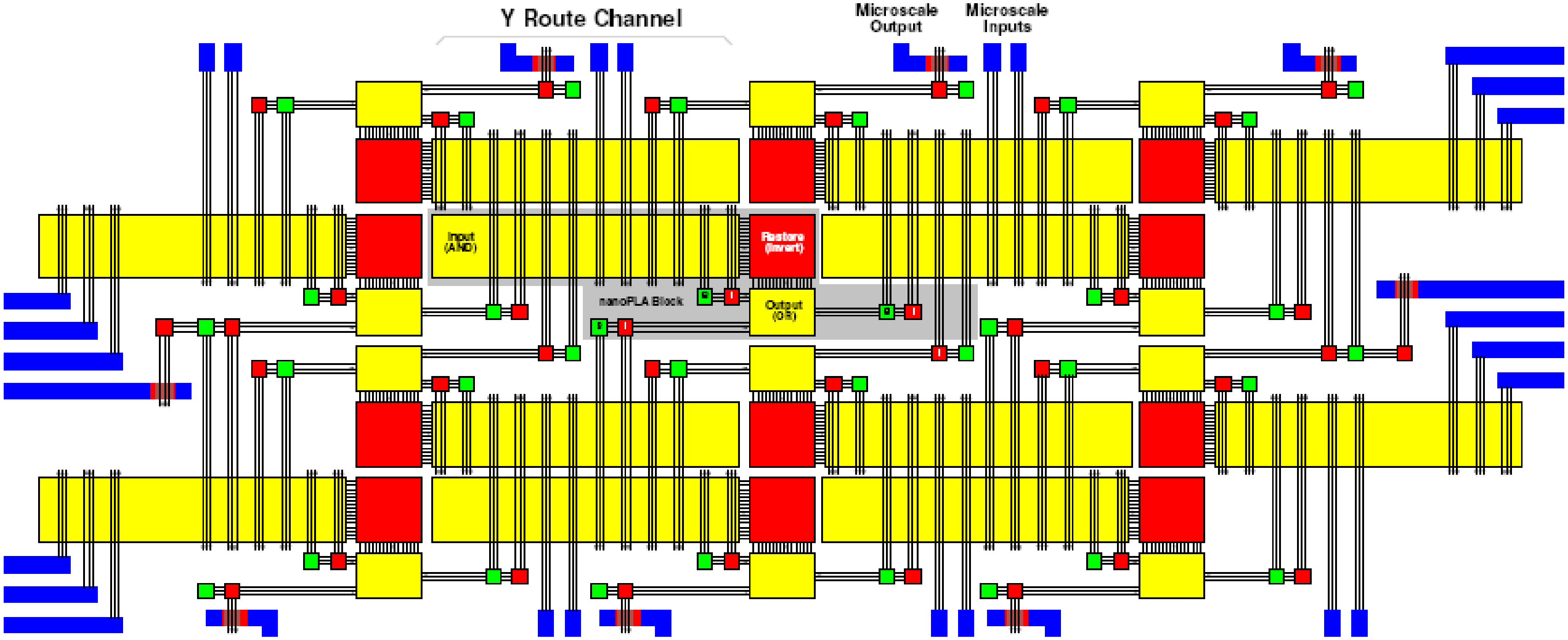


Logical Architectures



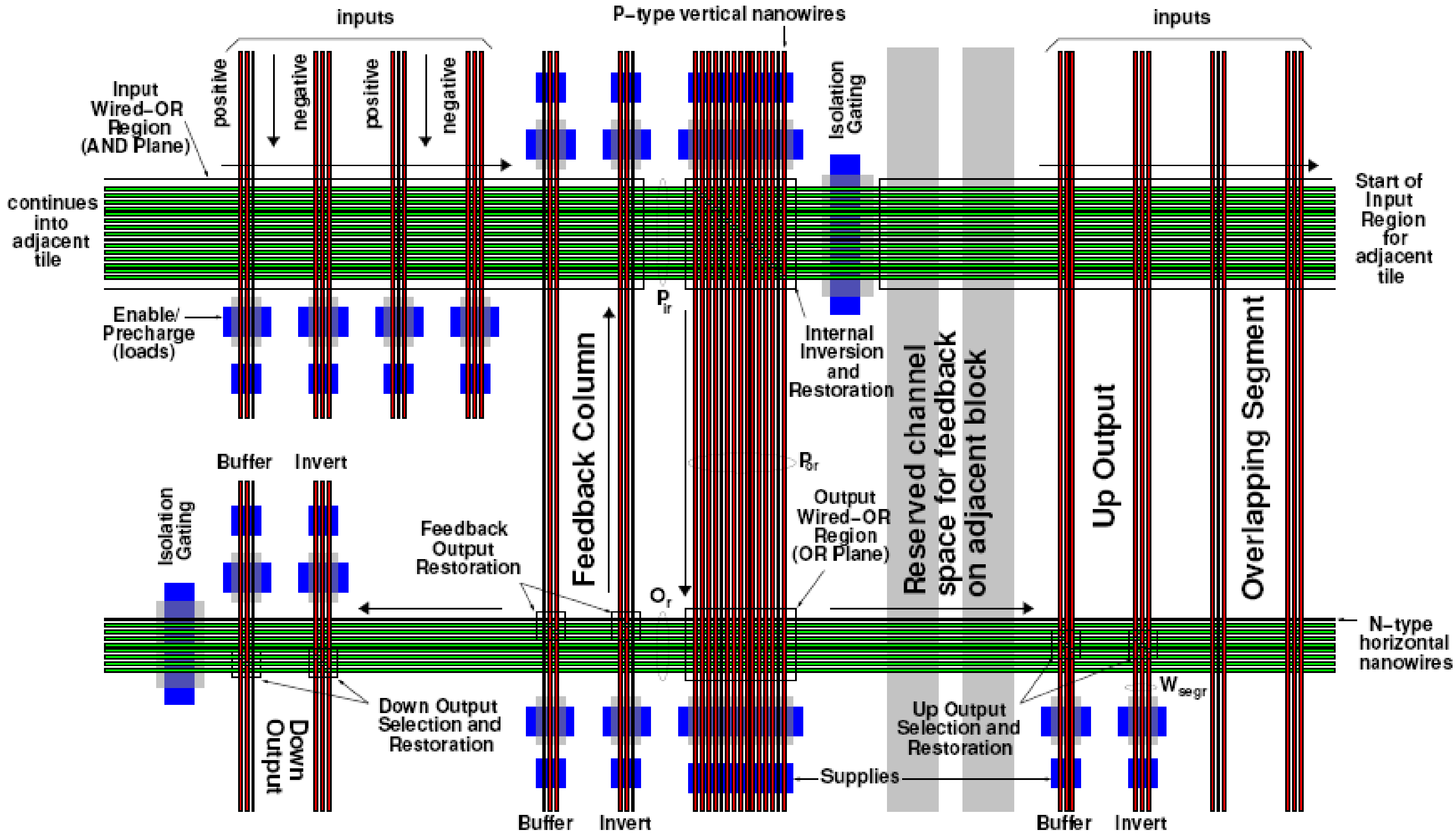
- PLA with two programmable and restoration/inversion sections
- Address discovery followed by programming
- Two-phase clocking will implement sequential logic

Interconnection of NanoPLAs



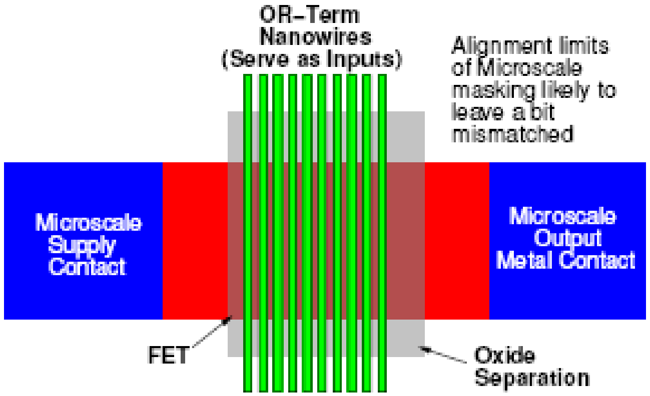
- Signal routing possible in X- and Y-direction as well as corner turning.

NanoPLA Block



Input/Output

- If NWs connected to CMOS wires, lots of time needed for charge accumulation
- Better solution: use many identically programmed NWs as collective FET
- How does one enter multiple independent inputs?



Defect Tolerance

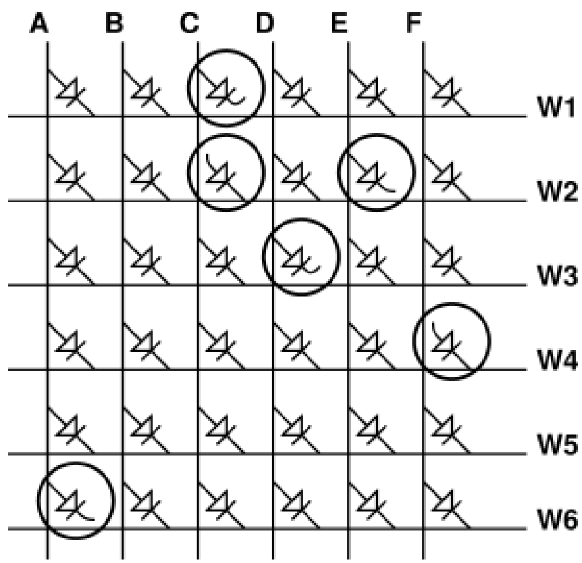
- NW sparing
  - Both OR output and restoration NWs must work correctly.
  - If P_w is prob NW is not defective, $(P_w)^2$ is prob that OR output is useable
  - How many NW pairs needed for correct operation?
- NW failure
  - P_c = prob NW makes good contact on one end
  - P_j = prob no break in NW of length L_0.
  - P_{ctrl} = prob NW aligned adequately
- For NW length $L = \rho\, L_0$, $P_w = (P_c)^2 \times (P_j)^\rho \times P_{ctrl}$
  - $P_w = .8$ is typical.

NW Yield Calculations

- No. non-defective wired-OR NWs
- No. uniquely addressable NWs
- No. non-defective restored NW pairs
- No. uniquely restored terms

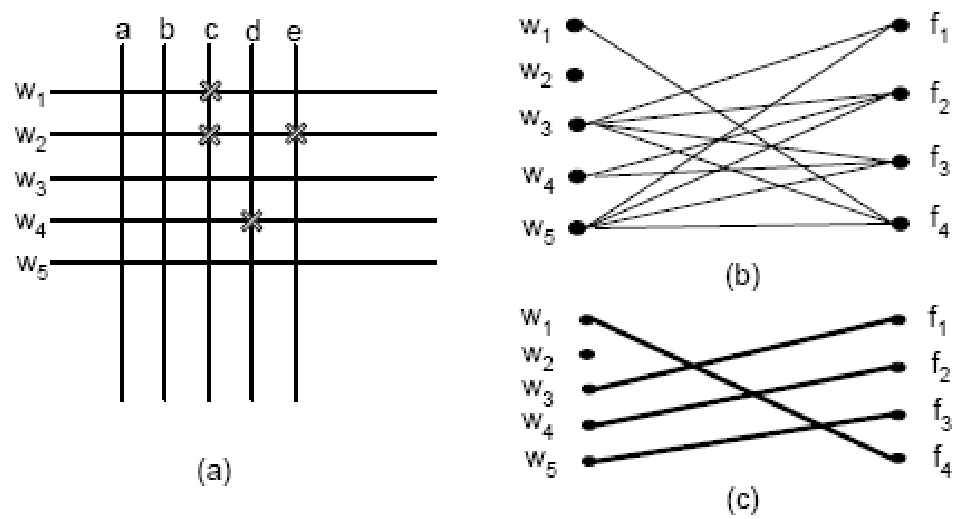
Defective Programmable Crosspoints

- Goal: reconfigure to route around defects
- E.g. OR-term $f = A+B+C+E$ can be assigned to W3 despite defect



Mapping OR-Terms to Crossbar with Defects

- This is a matching problem.
  - Fig (a) shows defects
  - Fig (b): NWs to which OR terms can be mapped
    - $f_1 = a+b+c+d$, $f_2 = a+c+e$, $f_3 = b+c$, $f_4 = d+e$
  - Fig (c): A matching

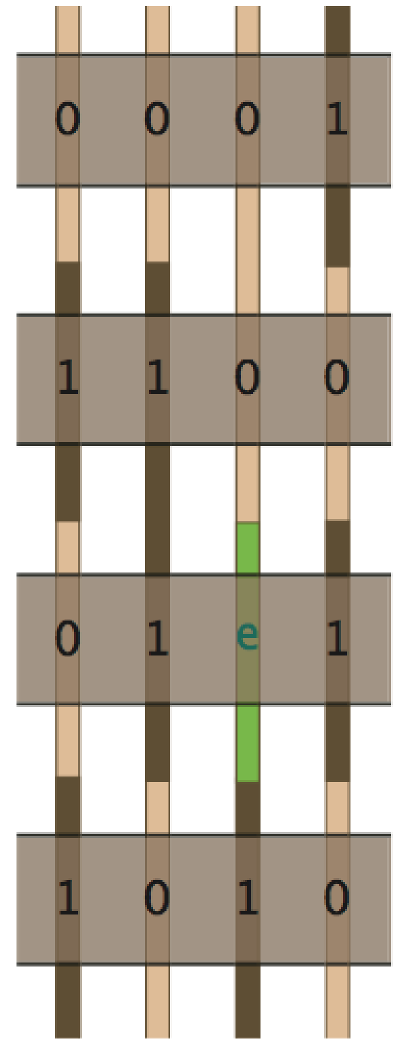


Imperfect NW Control

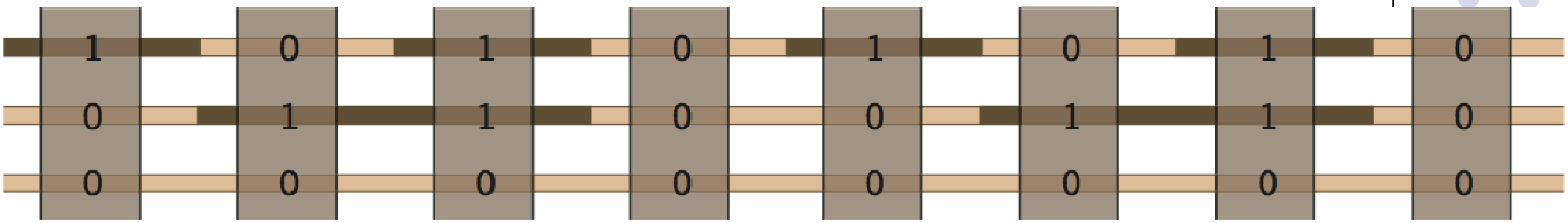
- Our binary model is accurate if each MW provides good control.
- Realistically, some MWs may only partially turn off some NWs.
- Also, some MWs may occasionally fail to control some NWs.
- Our decoders must be fault-tolerant!

Ideal Decoders with Errors

- To apply the ideal model to real-world decoders, consider binary codewords with random **errors**.
- If $c_{ij} = e$, the j^{th} MW increases n_i's resistance by an unknown amount.
- Consider input ***A*** such that the j^{th} MW carries a field. ***A*** functions reliably if a MW for which $c_{ik} = 1$ carries a field.



Balanced Hamming Distance



- Consider two error-free codewords, c_a and c_b. Let $|c_a - c_b]$ denote the number of inputs for which $c_{aj} = 1$ and $c_{bj} = 0$.
- The balanced Hamming distance (BHD) between c_a and c_b is $2 \bullet \min(|c_a - c_b], |c_b - c_a])$.
- If c_a and c_b have a BHD of $2d + 2$ they can collectively tolerate up to d errors.

Fault-Tolerant Random Particle Decoders

- In a randomized-contact decoder, $c_{ij} = 1$ with some fixed probability, *p*.
- If each pair of codeword has a BHD of at least $2d + 2$, the decoder can tolerate *d* errors per pair.
- This holds with probability $> 1- f$ when

$$M > \frac{\left(d + \left(d^2 + 4\, ln(N^2/f)\right)^{1/2}\right)^2}{4p(1 - p)}$$