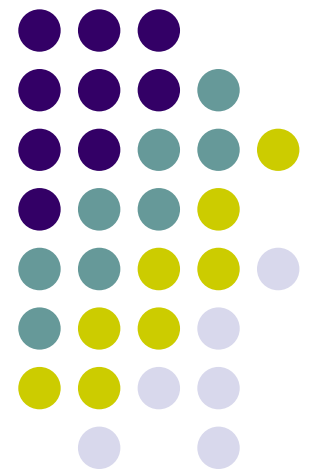


CSCI 2570

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 $22nm$ lithography, even if latter components are defect-free!



NW Properties

- Axially doped NWs
 - Resistance: $0.1\text{M}\Omega$ (on) to $10\text{G}\Omega$ (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 = $10^{-5}\ \Omega\text{cm}$, of Si = $10^{-3}\ \Omega\text{cm}$
 - This reduces NW contact resistance to $10\text{K}\Omega$



Demonstration Project

- Chen et al. [\[2003\]](#):
- Ti/Pt-[2] rotaxane-Ti/Pt sandwich exhibiting state storage with resistance change by $> \times 10$
 - From $500\text{K}\Omega$ to $9\text{M}\Omega$ for 1600nm^2 jnctn
- State switched with $\pm 2\text{V}$, read at $\pm 0.2\text{V}$
- Molecular sandwich created with Langmuir-Blodgett
- 8×8 crossbar constructed



Area/Length Comparisons

- SRAM-based programmable crosspoint has area $2,500\lambda^2$ versus $25\lambda^2$ for NW crossing [DeHon 1996].
- NWs can be grown to hundreds of microns in length, but only for large NWs.
 - $10\mu\text{m} \times 10\mu\text{m}$ arrays have been demonstrated

Defects in Wires and Crosspoints



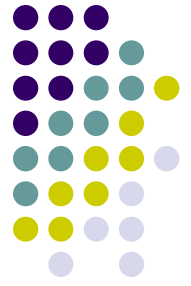
- NWs may break during assembly
 - Diameter can be ≈ 100 atoms
- Statistical nature of contacts
 - NW-to-MW junctions: small no. of atomic bonds
 - E.g. [\[Huang 2001\]](#): 95% of contacts good
 - NW-to-NW junctions: composed of 10s of atoms
 - E.g. [\[Chen 2003\]](#): 85% of crosspoints useable
- Statistical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



Defect Models

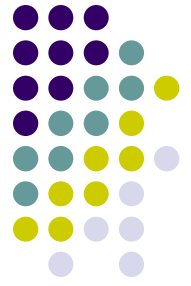
- **NW Defects**
 - Functional: Good contacts at each end, resistance within range, no shorts to other NWs
 - Defective NWs can be found through testing
 - Shells on axial or radial NWs prevent shorts between NWs
- **Crosspoint Defects**
 - Programmable (Most common state)
 - Resistance can be switched 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 $1 \mu\text{m}^2$ area, density of $6.4 \text{ Gbits cm}^{-2}$. 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
- [\[Wu 2005\]](#) 34×34 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

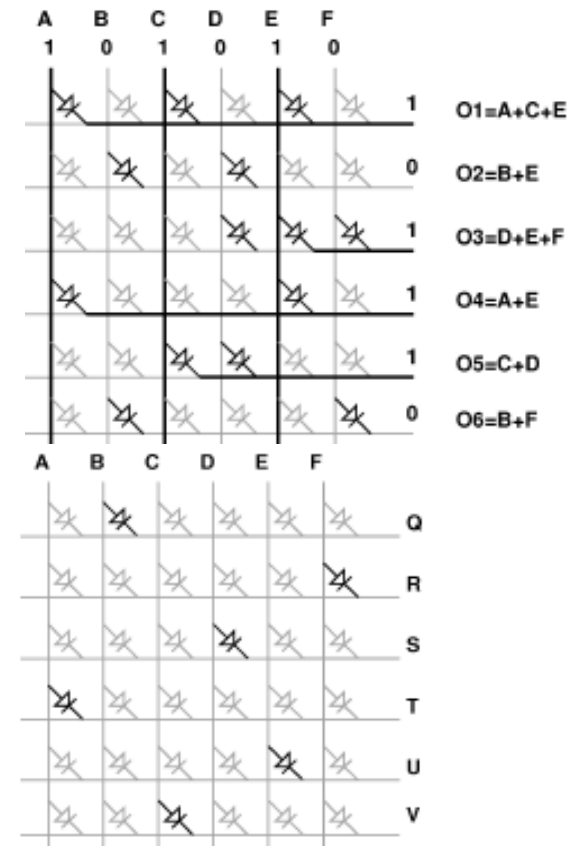


- [Heath and Stoddart](#) have implemented a 400x400 array of NWs with density of 10^{11} bits/centimeter.
 - “Modern DRAM circuits have 140nm pitch wires and a memory cell size of 0.0408 mm^2 .”
 - “Here we describe a 160,000-bit molecular electronic memory circuit, fabricated at a density of 10^{11} 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



@ JETC, Vol. 1, No. 2, 2005



NW Encoding and Decoding

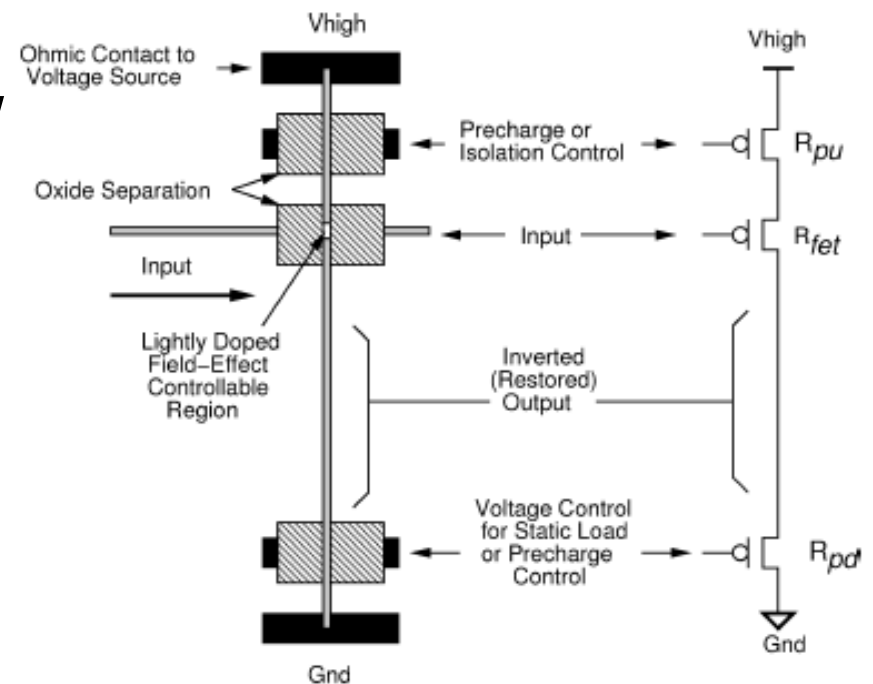
- Goal: turn on one NW in each array dimension
- Earlier lectures describe
 - Undifferentiated NW decoders
 - Random contact decoder
 - Randomized mask-based decoder
 - Differentiated NW decoders
 - Axially encoded NWs
 - Radially encoded NWs

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

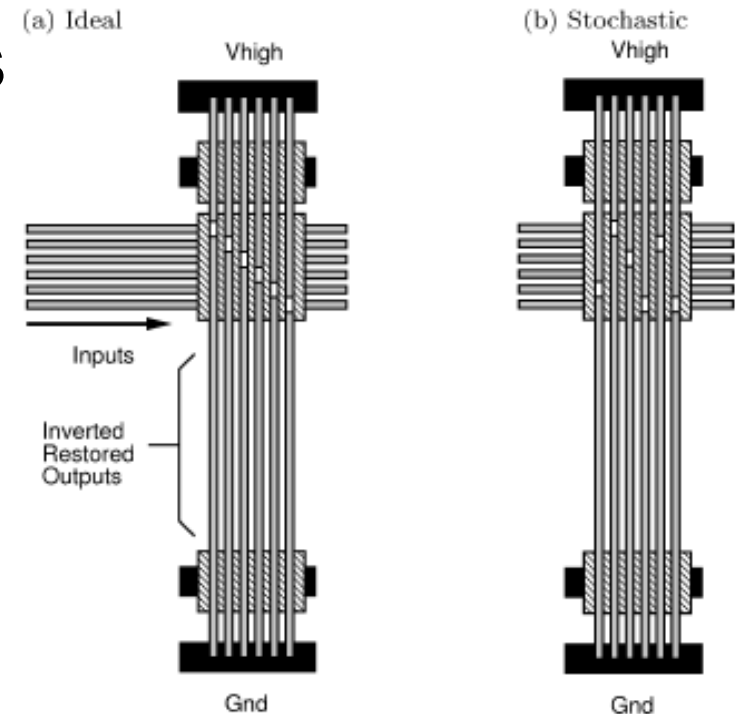
$$V_{out} = V_{high} \left(\frac{R_{pd}}{R_{pd} + R_{fet}(Input) + R_{pu}} \right)$$



@ JETC, Vol. 1, No. 2, 2005

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

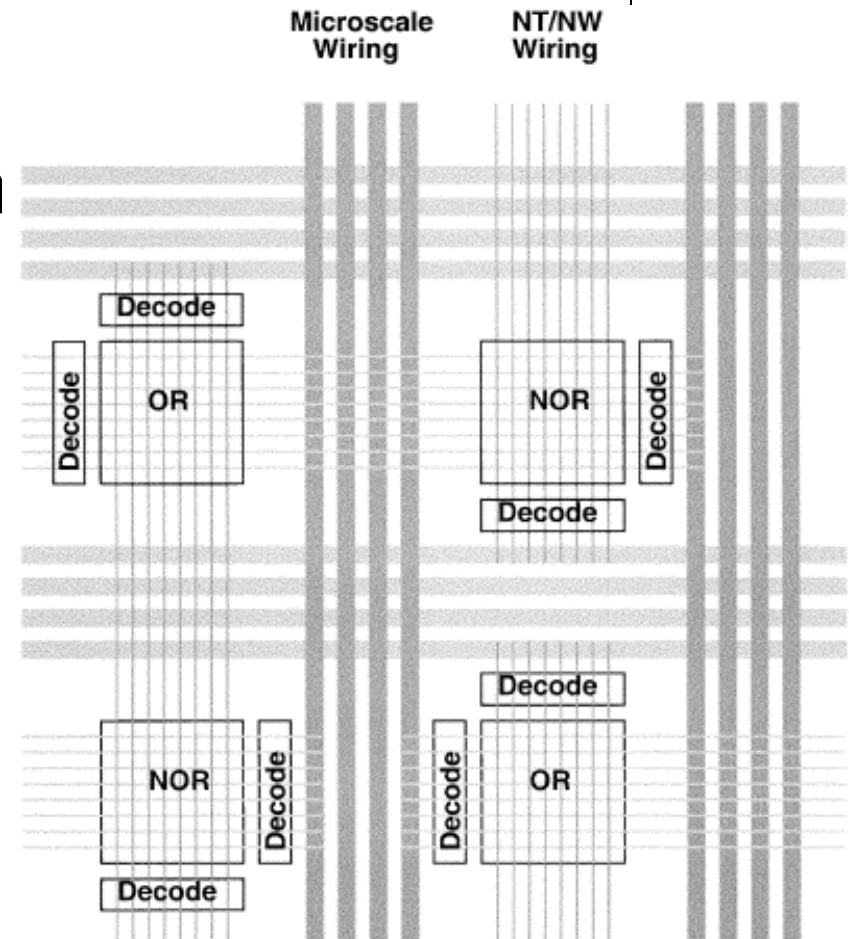


@ JETC, Vol. 1, No. 2, 2005



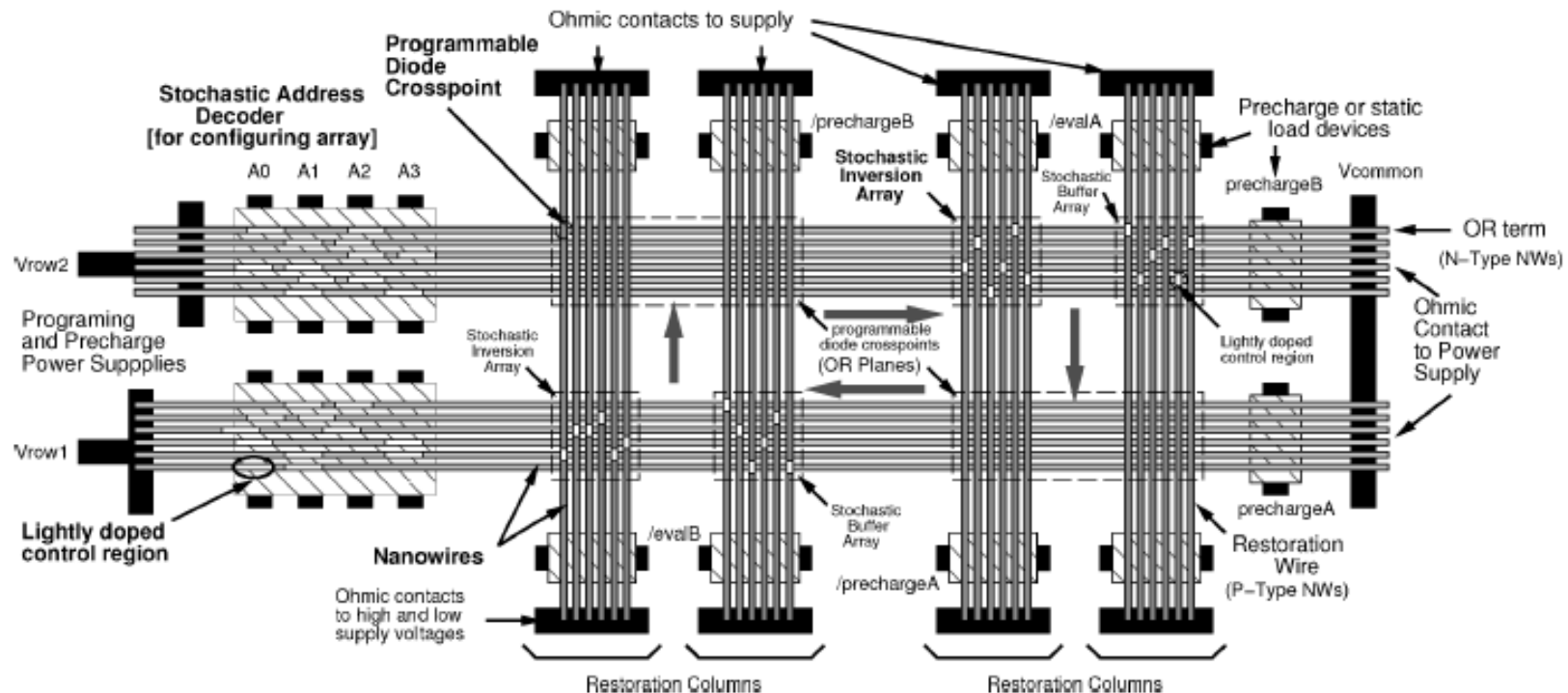
Array-Based Architectures

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

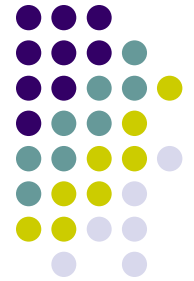




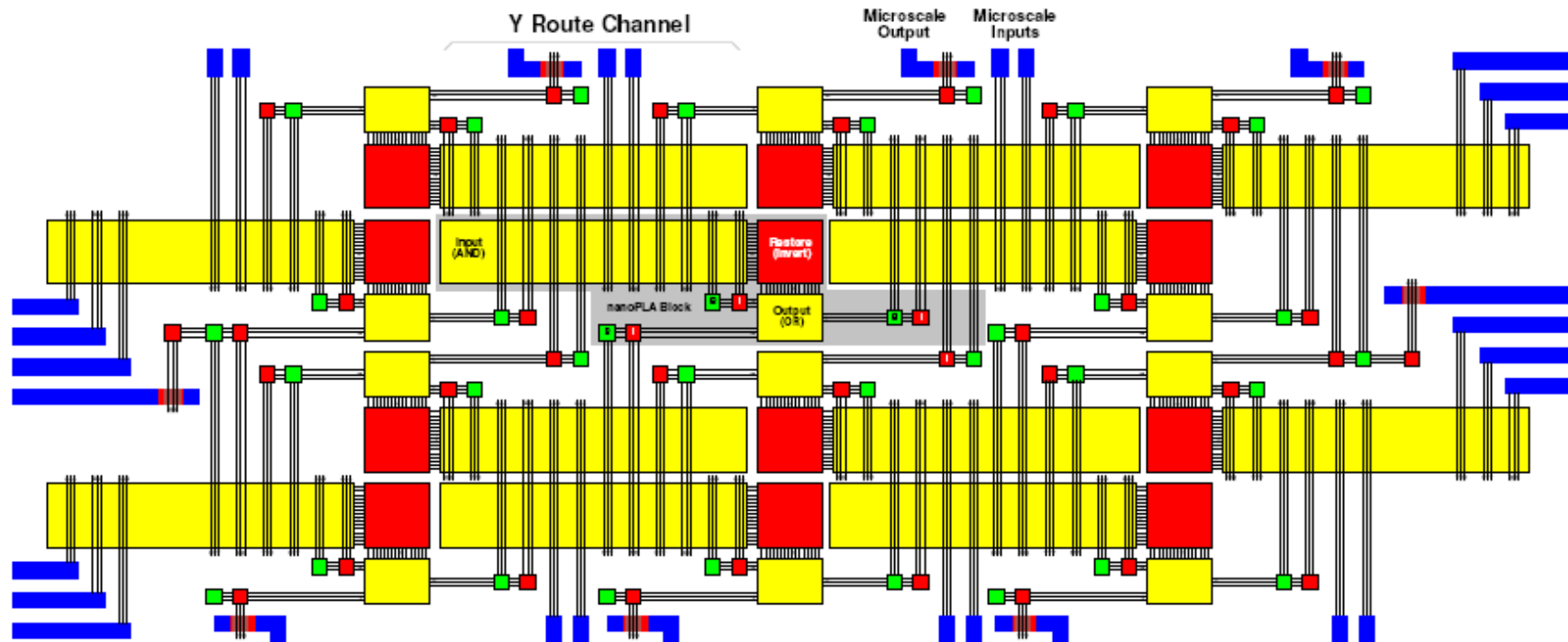
Logical Architectures



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



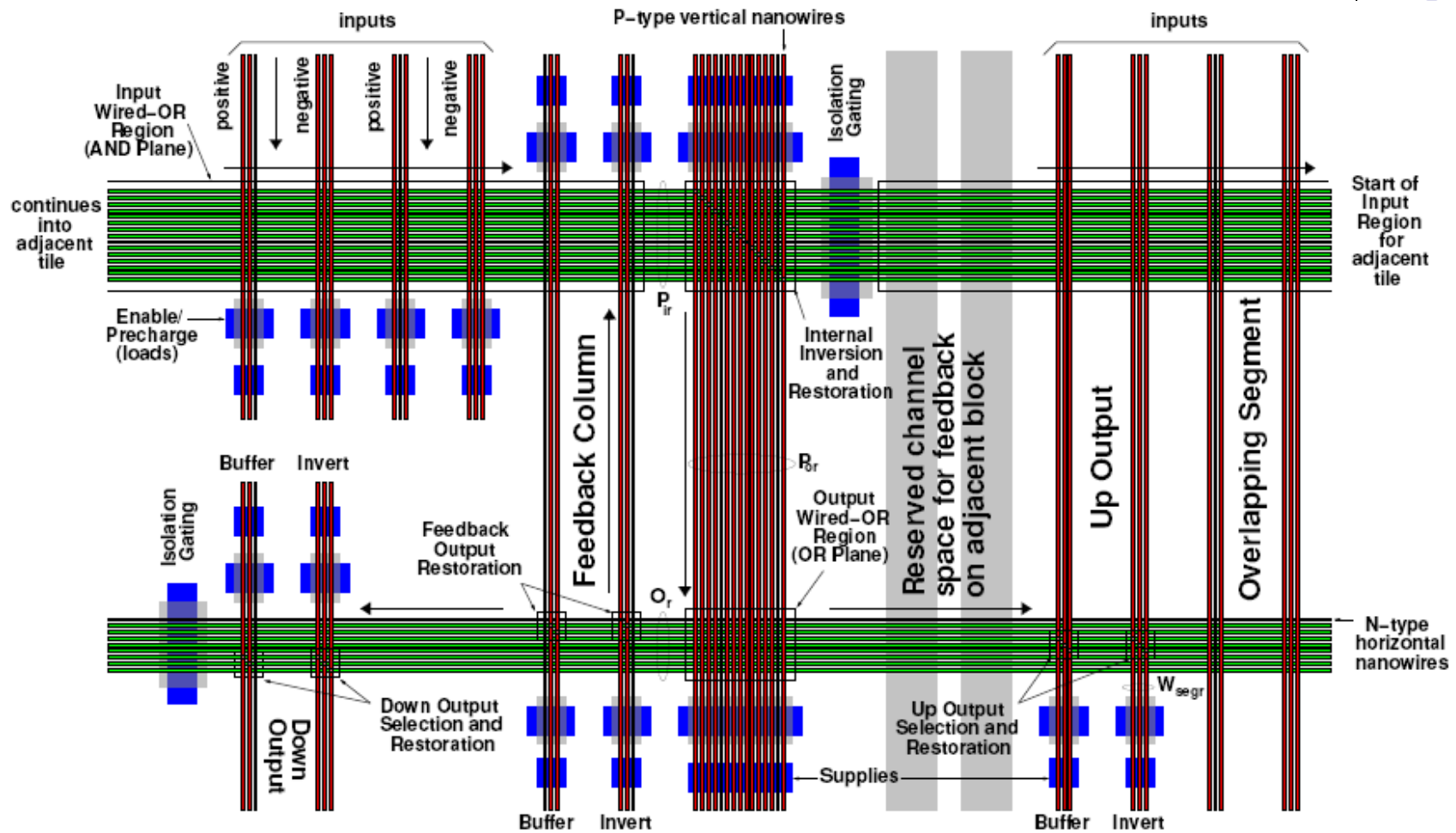
Interconnection of NanoPLAs



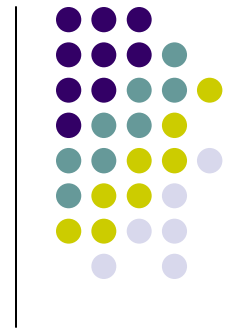
- Signal routing possible in X- and Y-direction as well as corner turning.



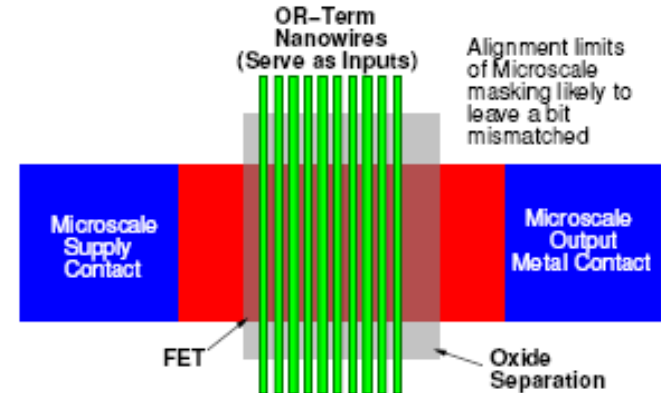
NanoPLA Block

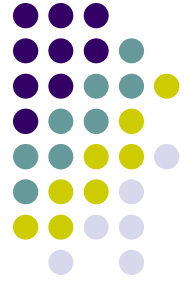


Input/Output



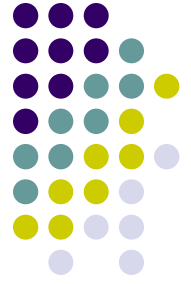
- If NWs connected to CMOS wires, lots of time needed for charge accumulation
- Better solution: use many identically programmed NWs as collective FET
- How does one enter multiple independent inputs?





Defect Tolerance

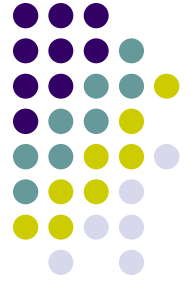
- NW sparing
 - Both OR output and restoration NWs must work correctly.
 - If P_w is prob NW is not defective, $(P_w)^2$ is prob that OR output is useable
 - How many NW pairs needed for correct operation?
- NW failure
 - P_c = prob NW makes good contact on one end
 - P_j = prob no break in NW of length 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.



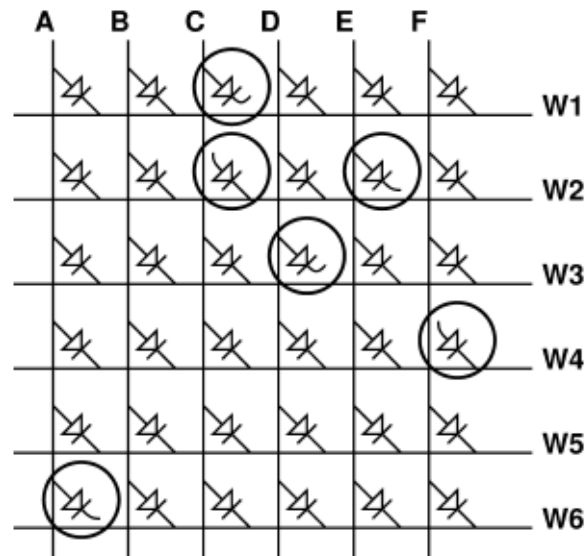
NW Yield Calculations

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

Defective Programmable Crosspoints



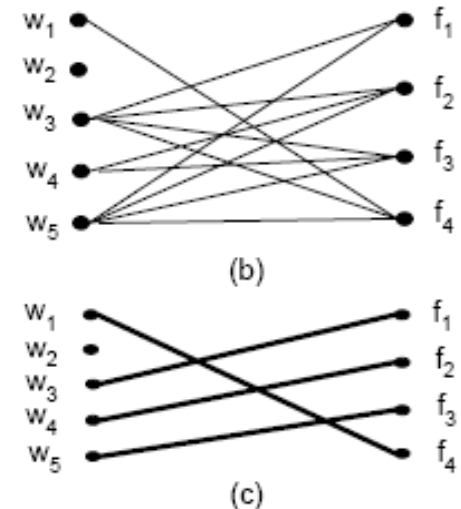
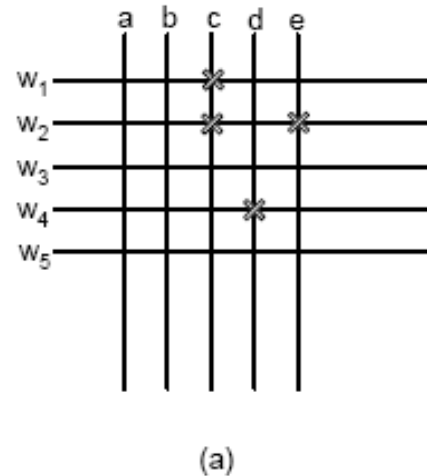
- Goal: reconfigure to route around defects
- E.g. OR-term $f = A+B+C+E$ can be assigned to W3 despite defect

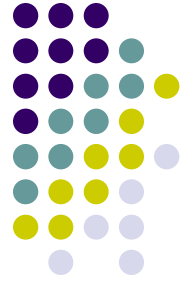


Mapping OR-Terms to Crossbar with Defects



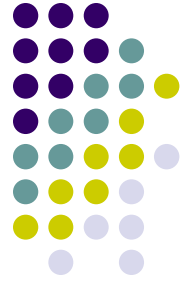
- This is a matching problem.
 - Fig (a) shows defects
 - Fig (b): NWs to which OR terms can be mapped
 - $f_1 = a+b+c+d$, $f_2 = a+c+e$, $f_3 = b+c$, $f_4 = d+e$
 - Fig (c): A matching





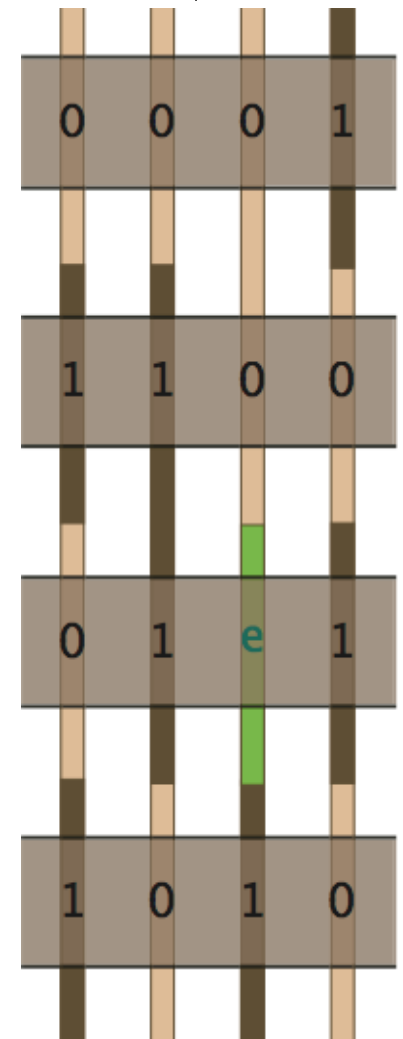
Imperfect NW Control

- 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!

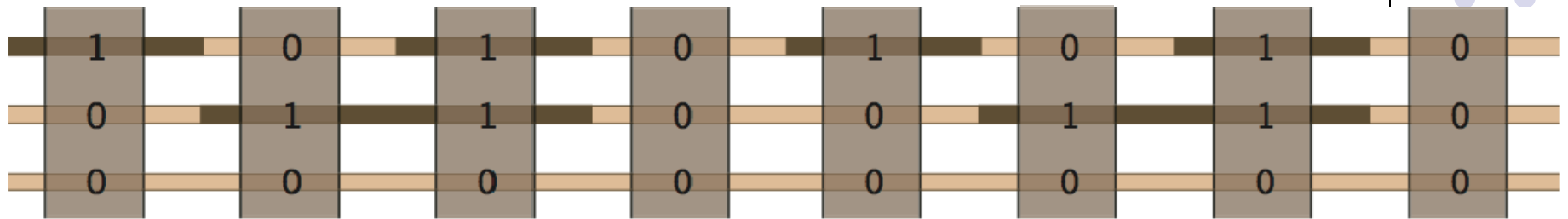
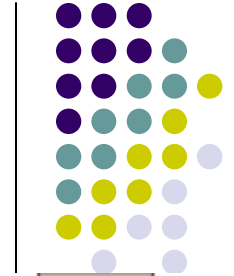


Ideal Decoders with Errors

- 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 $2 \cdot \min(|c_a - c_b|, |c_b - c_a|)$.
- 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

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