The State of ZettaRAM

Eric Rotenberg and Ravi K. Venkatesan*

Center for Embedded Systems Research (CESR)
Department of Electrical and Computer Engineering
North Carolina State University
www.tinker.ncsu.edu/ericro

* Now at Intel Bangalore

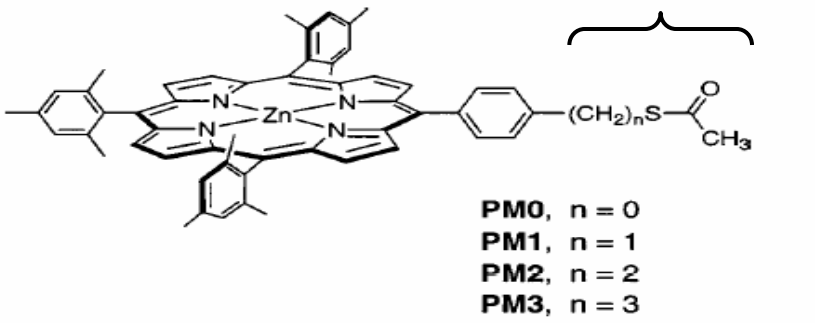
Goal of Talk

- High level (casual) talk about ZettaRAM
- Consolidate papers and patents
  - Core technology
  - Three different embodiments
  - Key novel properties
  - Implications

Core Technology

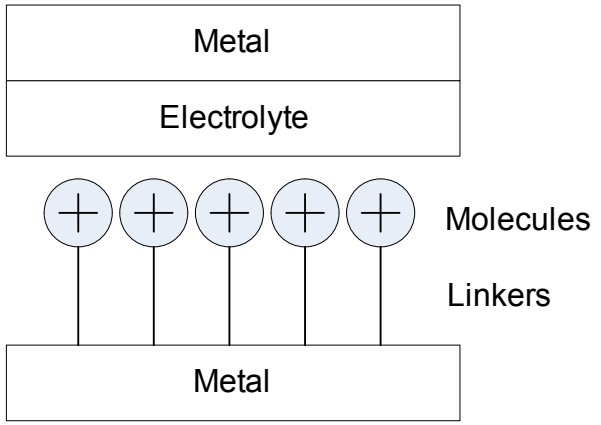
- New memory from ZettaCore
  - Genesis in DARPA Moletronics
  - Molecule stores 1 charge (0, +1)
  - Some molecule types store multiple charges (0, +1, +2)

Porphyrin Molecule



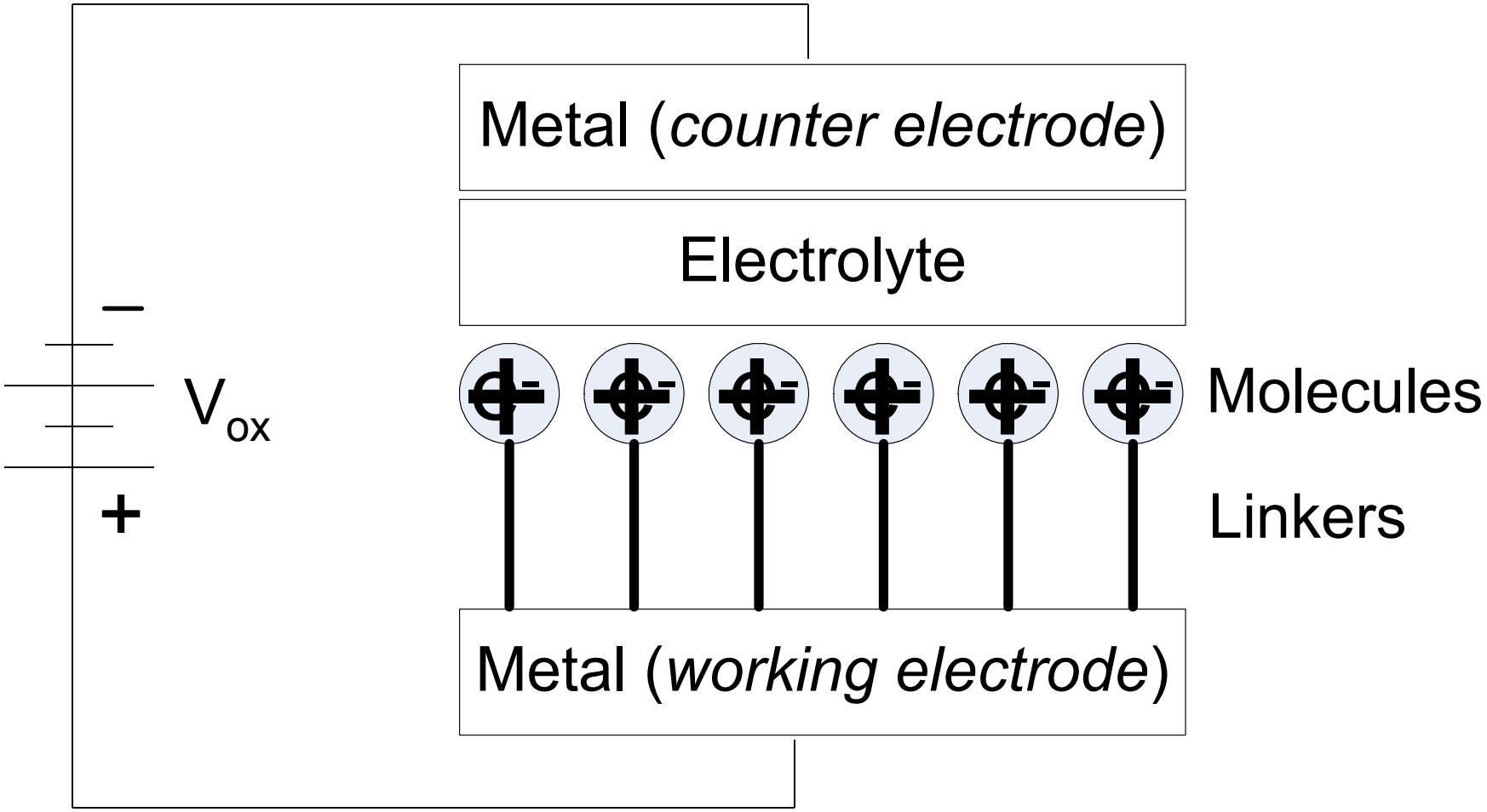
- Long term
  - 1 molecule = 1 bit

ZettaRAM Molecular Capacitor



- Near term
  - Use molecules in aggregate
  - Molecular capacitor

Molecular Capacitor



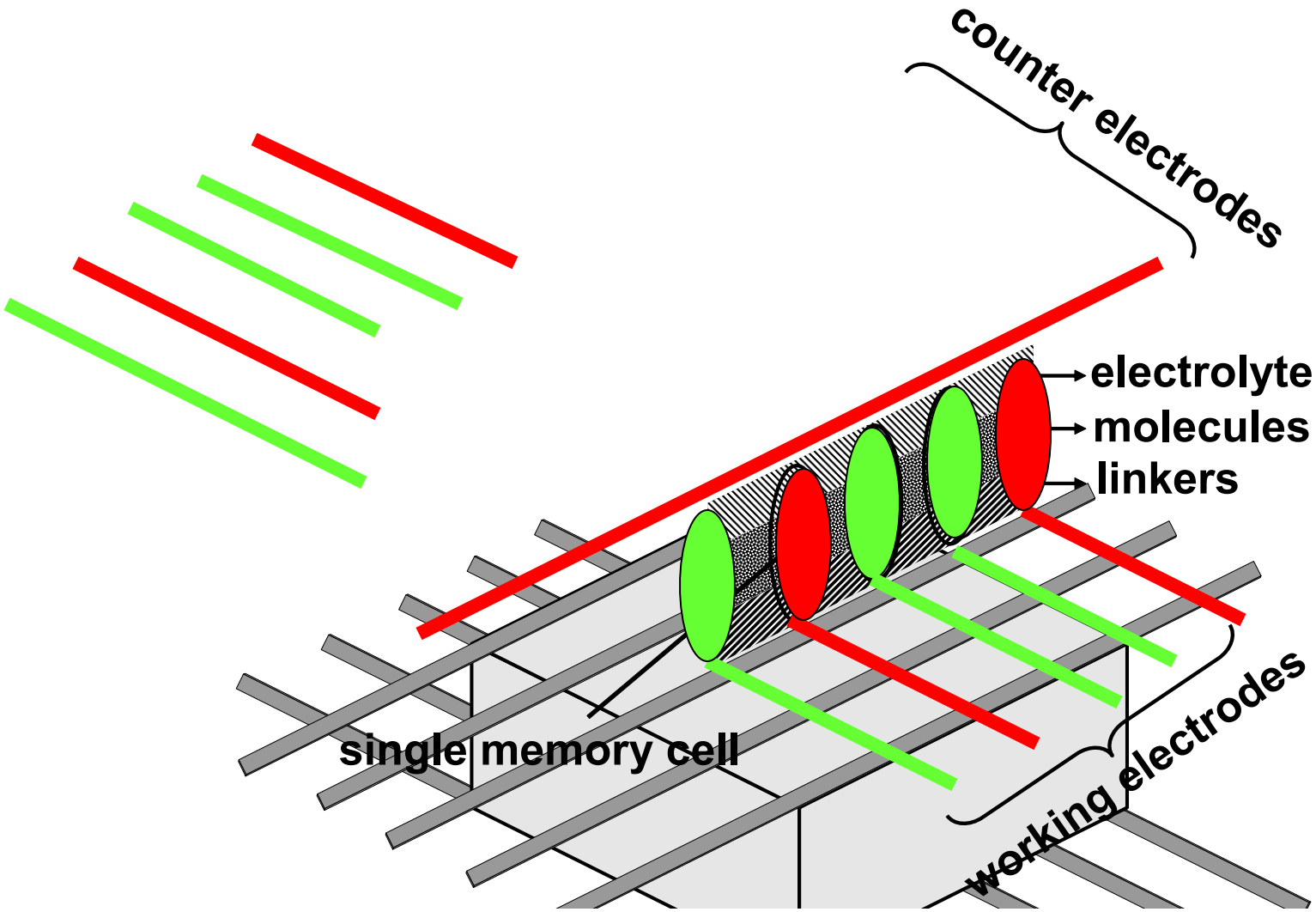
Linker & Electrolyte

- Neither conduct electrons
- Electrons tunnel across linker
- Electrolyte ions form aligned dipoles
  - Electrically interface counter electrode to molecules, yet charged molecules isolated
  - Also provide critical charge shielding, prevent huge electric field across short linkers
- Intrinsic retention times of 10s of seconds to minutes

Three Embodiments

- Transistor-free **Crossbar**
- Two hybrid molecule/silicon devices
  - Flash-like **MoleFET**
  - **1T-1C DRAM cell** with molecular capacitor

Crossbar


counter electrodes
electrolyte
molecules
linkers
single memory cell
working electrodes

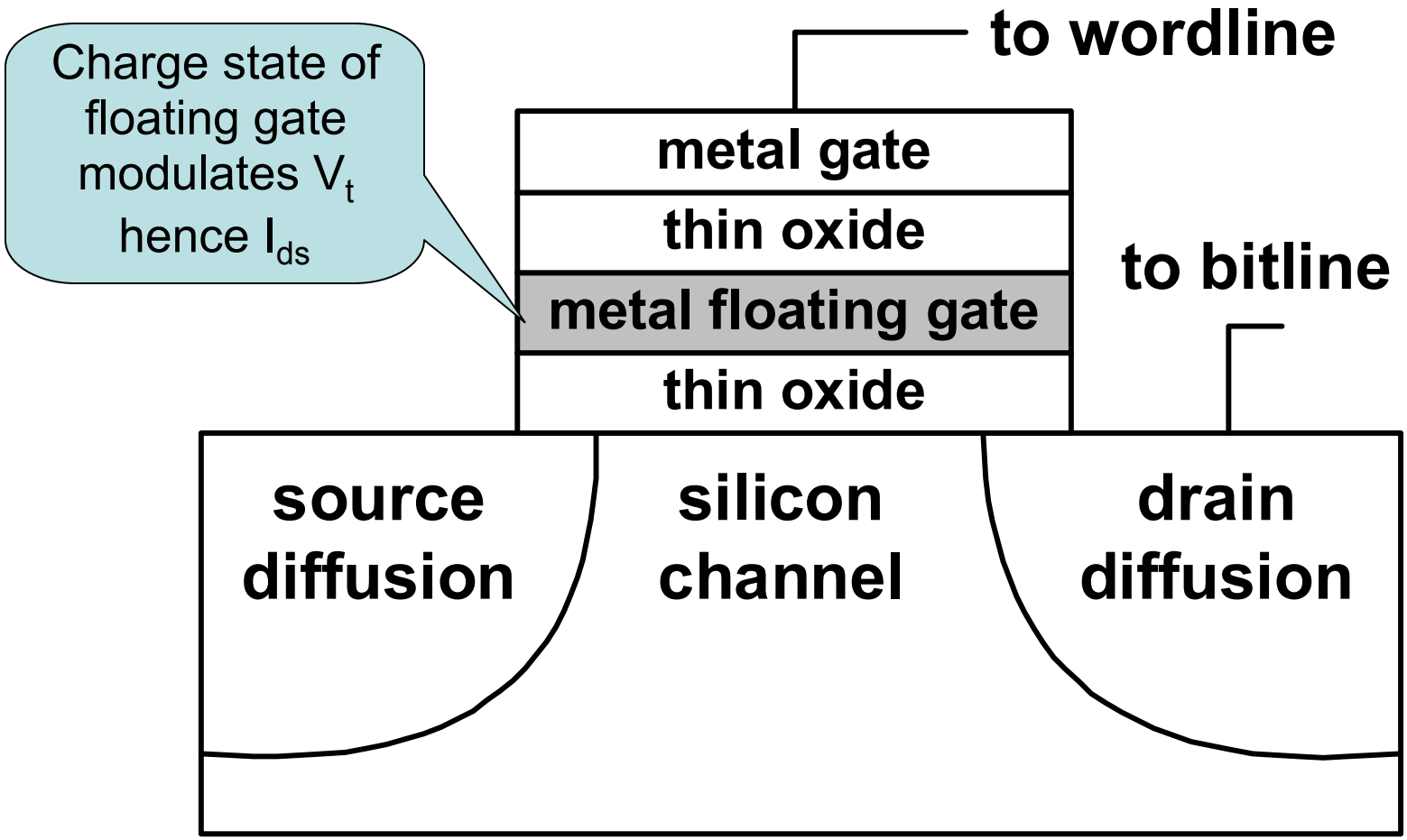
Crossbar Features

- No explicit patterning of cells
  - Cell forms implicitly between electrodes
  - Density only limited by wire pitch
  - Easy path to minimum DRAM density
- Silicon free
  - Easy 3D stacking (no silicon growth)
  - Deposit on arbitrary surfaces? Flexible memory?

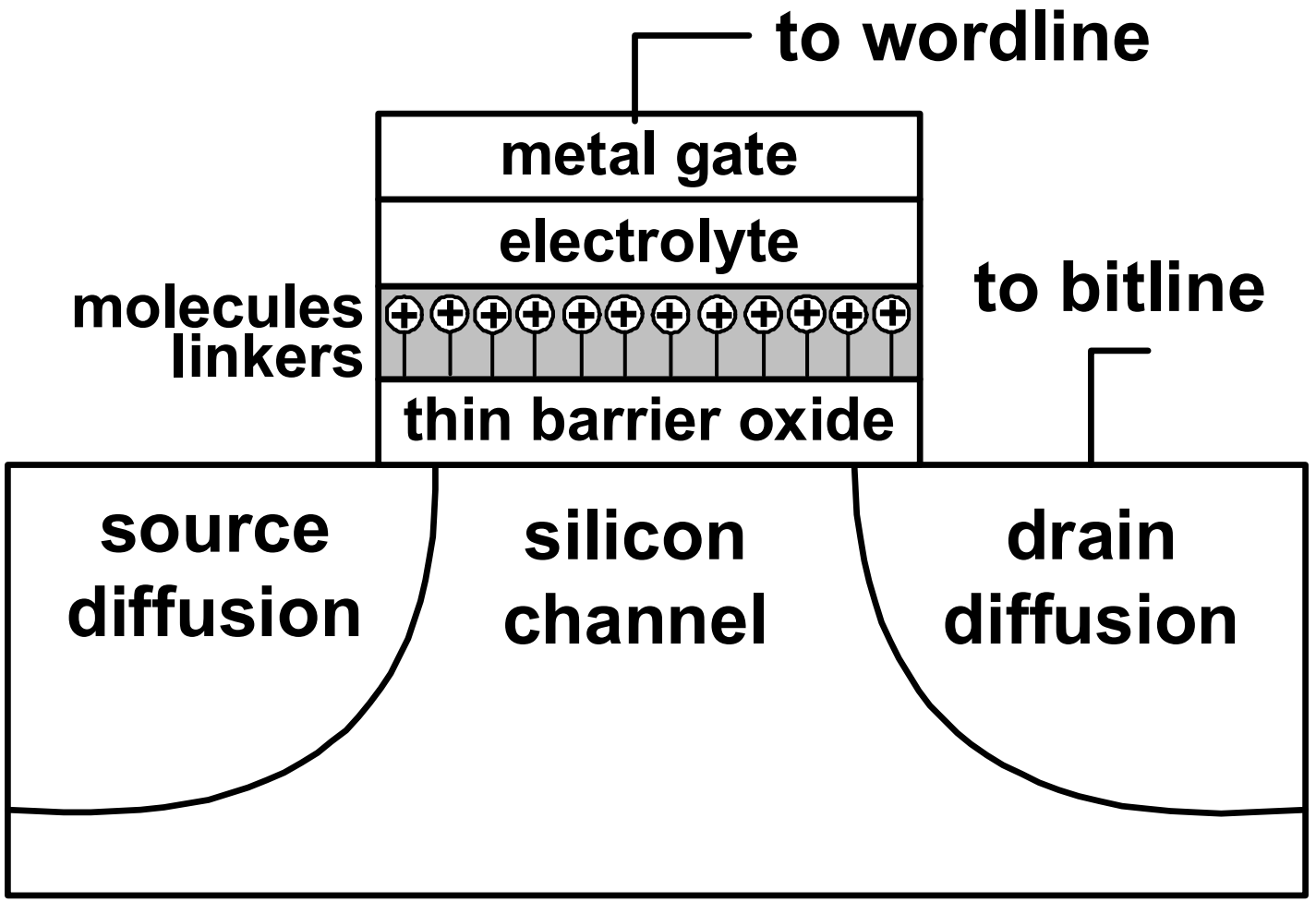
Crossbar Fate

- Crossbar earliest embodiment
- 2x2 in the lab
- Repeatability issues?
  - Disturbs due to floating electrode voltages
  - Better control with transistor switches at intersections
- Meanwhile
  - Moletronics 2nd phase brought transistor fab engineers
  - Shift towards hybrid molecules/silicon
  - Leverage predominance of silicon fabrication

Conventional Flash Memory

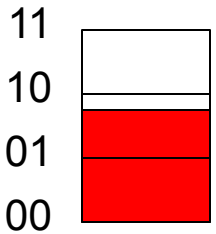


MoleFET Flash Memory

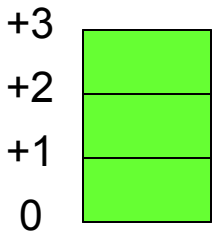


MoleFET Features

- Fixed charge provides discreteness
  - Remarkable accuracy compared to “continuous” floating gate
  - Robust, work within tighter noise margins
  - Path to smaller devices
- Discreteness especially benefits multi-bit storage
  - Multi-bit successful in Flash domain
  - Molecules with multiple discrete charge states makes multi-bit much easier



Flash



MoleFET

$V_{prog} > V_{ox3}$

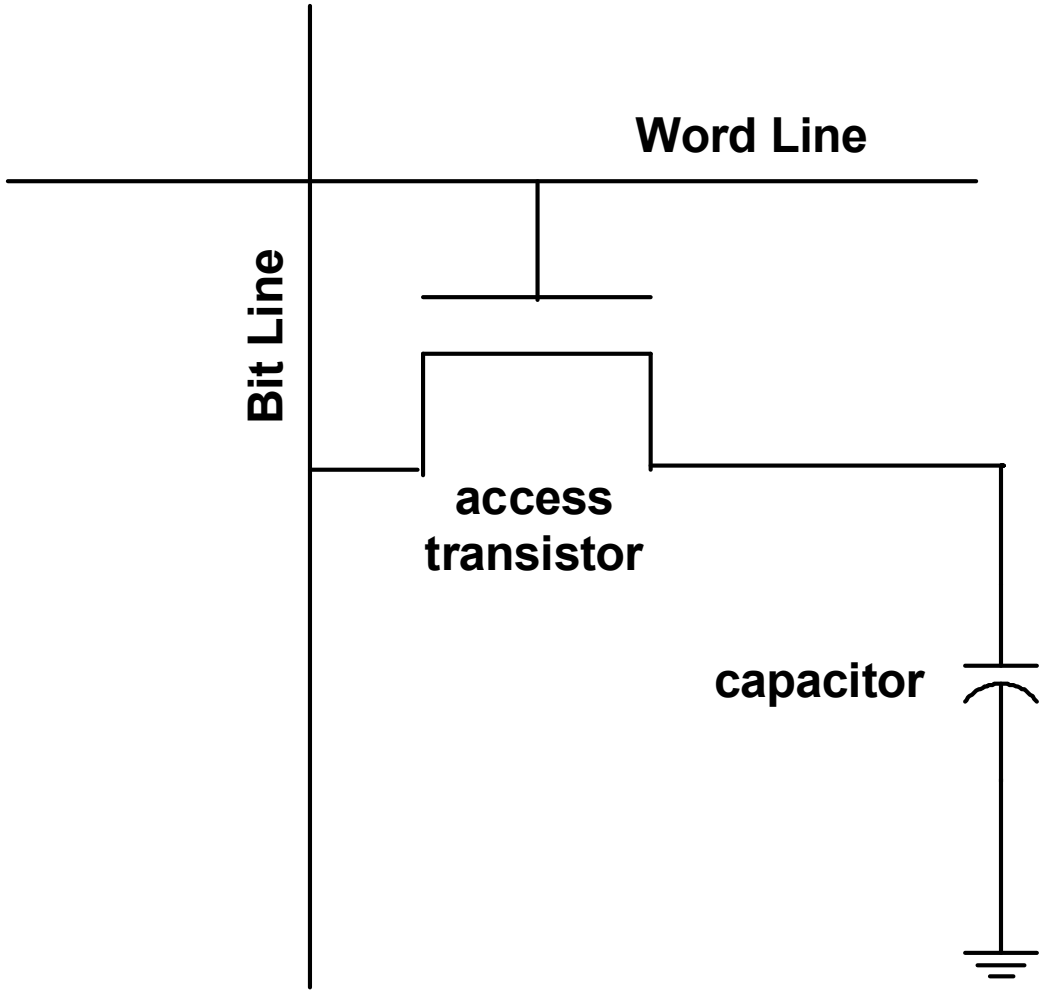
$V_{prog} > V_{ox2}$

$V_{prog} > V_{ox1}$

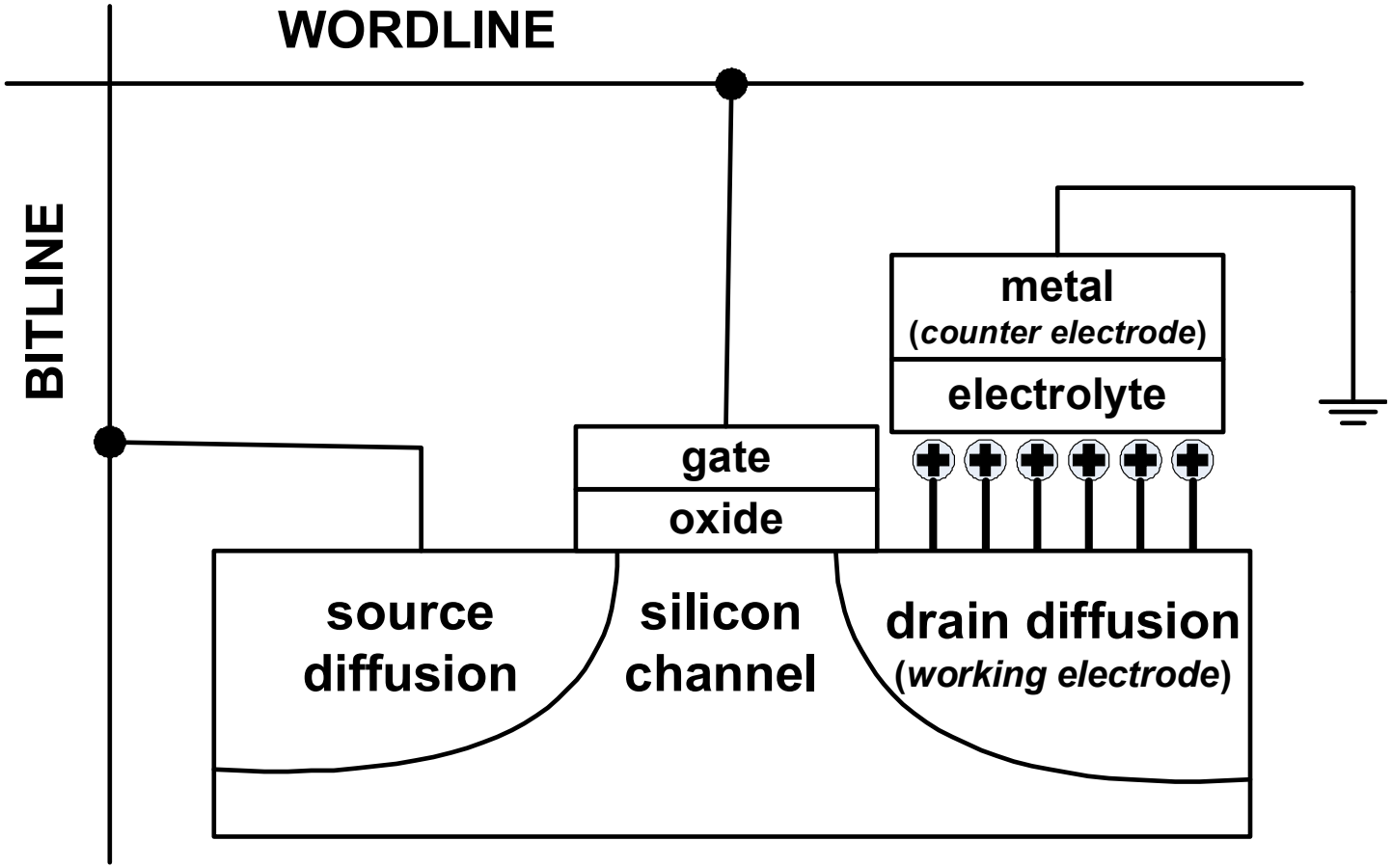
MoleFET Issues

- Striving for larger V_t shift

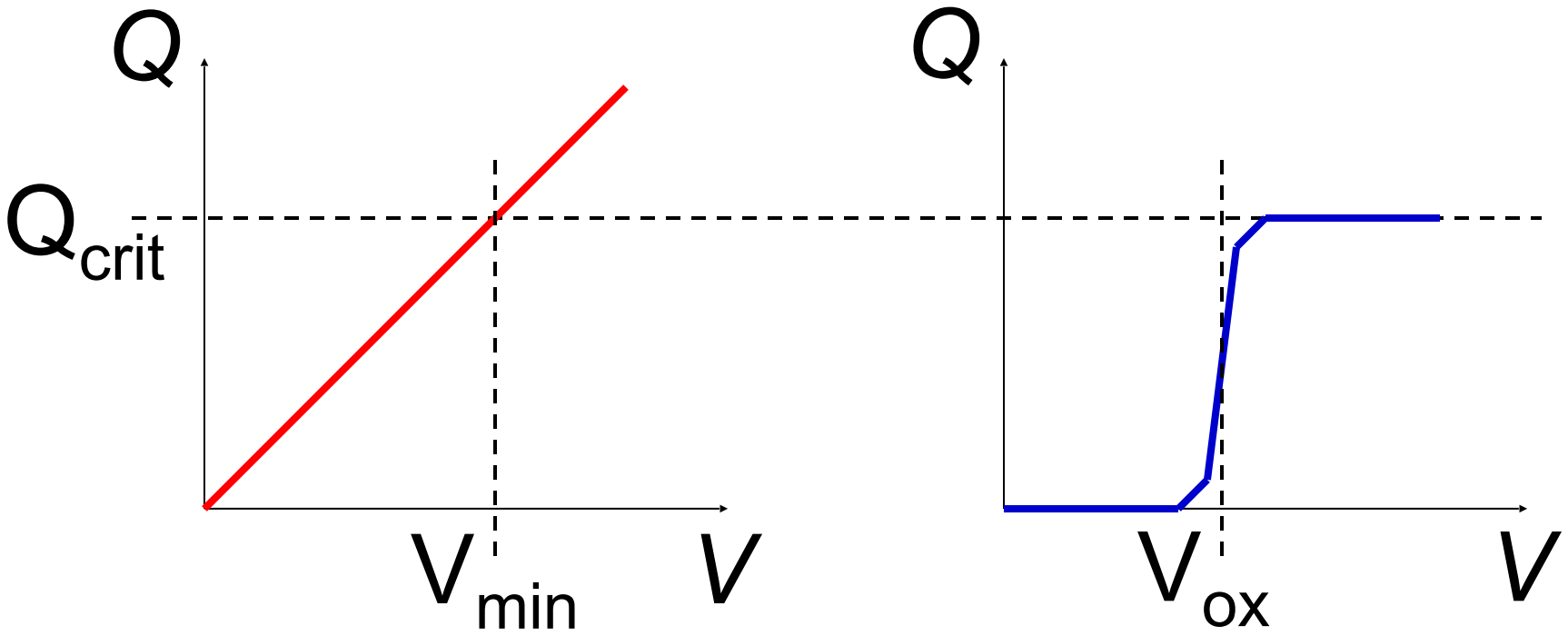
Conventional 1T-1C DRAM Cell



1T-1C DRAM Derivative



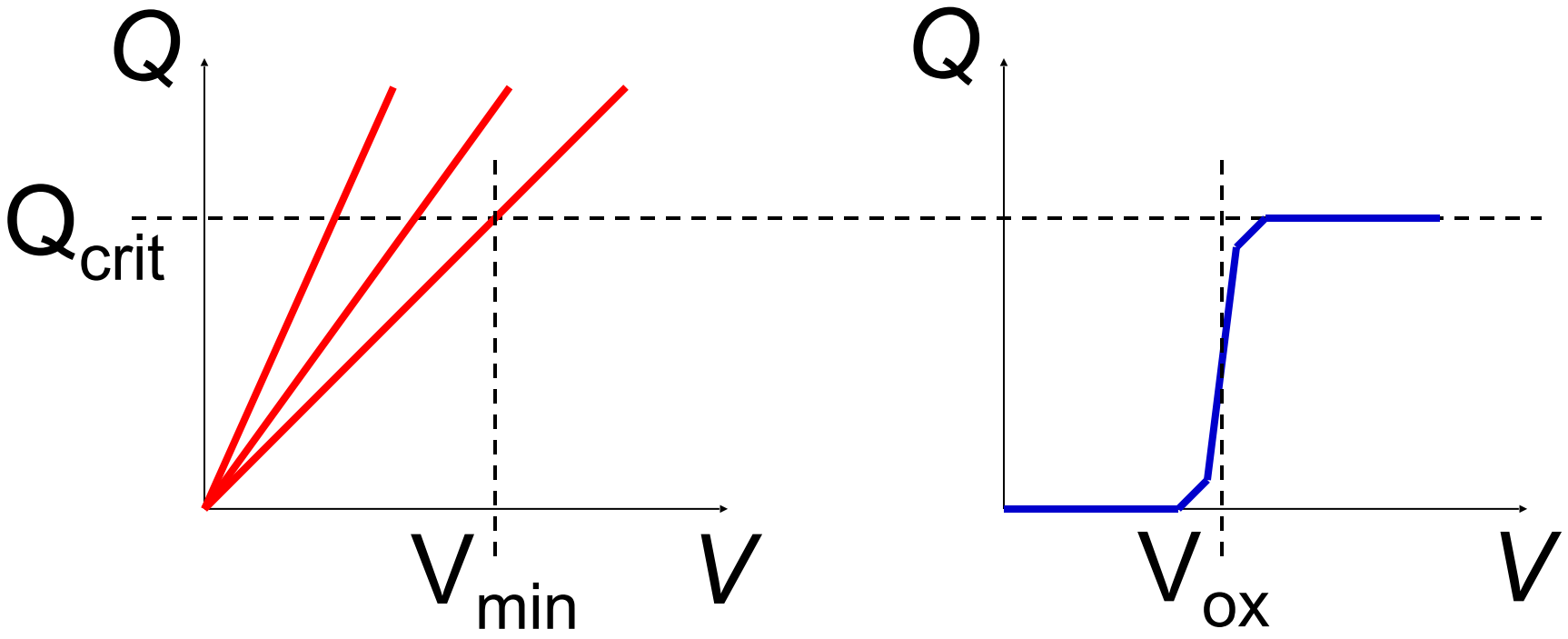
DRAM Voltage Scaling Limits



ZettaRAM's Power Scaling Advantage

- Q_{crit} nearly constant due to noise sources
  - Sense amp margins
  - Bitline imbalances
  - Leakage
  - Radiation
- Conventional DRAM
  - Charge-voltage coupling, Q = CV
  - Charge constrains voltage
- ZettaRAM derivative
  - Charge-voltage decoupling
  - Fixed charge independent of voltage
  - Charge does not constrain voltage

DRAM Voltage Scaling Limits



- Hard to increase C
- Even harder when reducing 2D area

- Engineer new molecules with lower thresholds

Key Properties

- Flexibility and Precision
- Self-Assembly
- Charge-Voltage Decoupling
- Speed/Energy Tradeoff
- Multiple Discrete States
- Admixtures

Flexibility and Precision

- Hundreds of molecules synthesized
- Significant flexibility in customizing molecular attributes
  - Design of organic molecules
  - Design of attachment groups
  - Influence surface concentration (density), threshold voltage (power), electron transfer rate (speed, retention time)
- Semiconductors also flexible
  - But attributes (e.g., threshold voltage) depend on bulk properties
  - Sophisticated “recipes” required
  - High cost to achieve precision
  - *Contrast bulk properties with intrinsic chemical properties of molecules*

Self-Assembly

- Auto arrangement of molecules in single, uniform, dense monolayer
  - Autonomous and parallel
  - Efficient fabrication
- Reconsider possibilities thought impractical with conventional tech.
- Mixed logic/DRAM chips (DRAM embodiment)
  - Conventional logic and DRAM processes too different due to stacked capacitors
  - Self-assembled monolayers yield high charge density without elaborate stacked capacitor structures
  - Apply thin oxide concept of MoleFET to reduce leakage (speed tradeoff)
- 3D stacking (crossbar embodiment)
  - Molecules self-assemble on any compatible surface
  - Easy path to 3D memory stacking

Charge-Voltage Decoupling

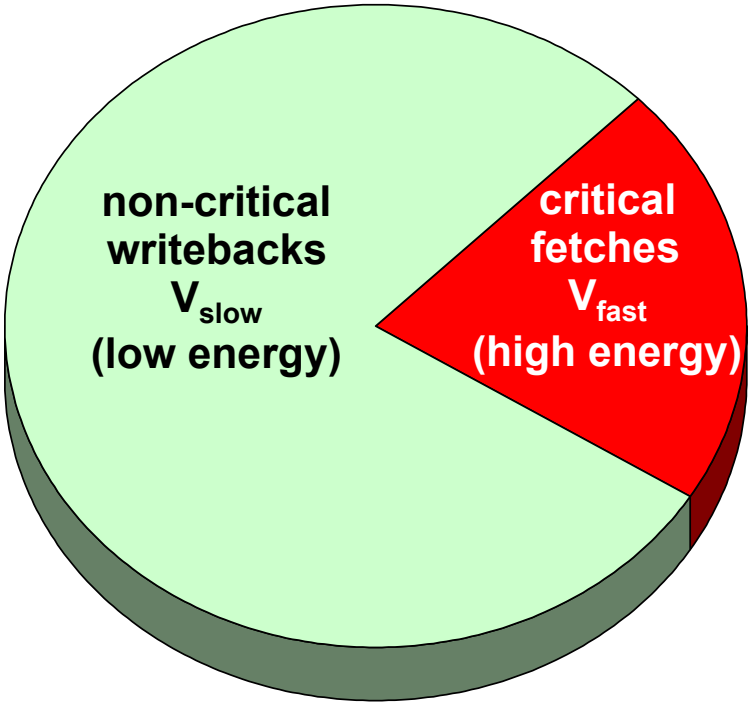
- Fixed charge independent of voltage
- Charge does not constrain voltage
- Power-scalable DRAM derivative extends roadmap of this important memory technology

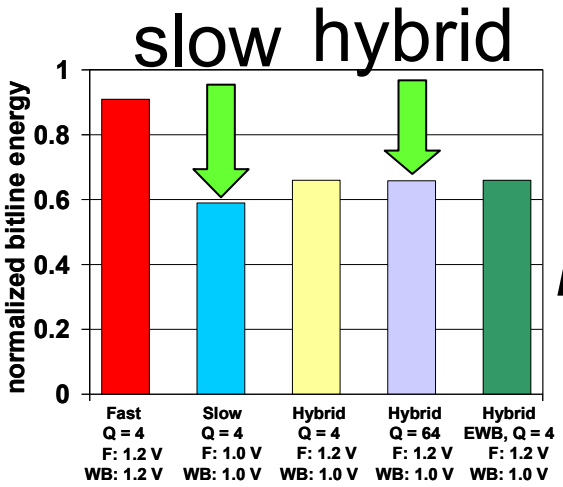
Speed/Energy Tradeoff

- Voltage padded with respect to V_{ox}
  - Molecule speed slower as voltage approaches V_{ox}
  - Pad write voltage for competitive latency
- Opportunity for architectural management
- Apply “fast voltage” for critical requests and “slow voltage” for non-critical requests

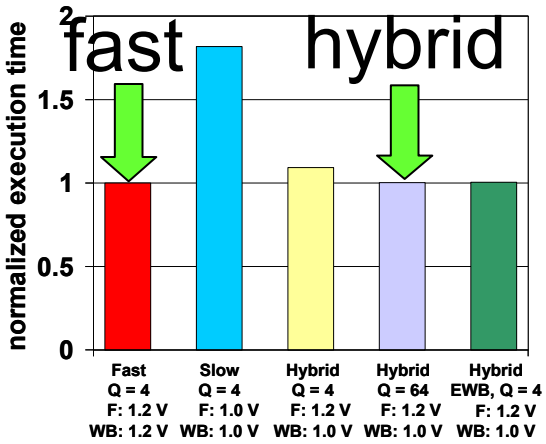
Intelligent Management

Hybrid Write Policy





Energy



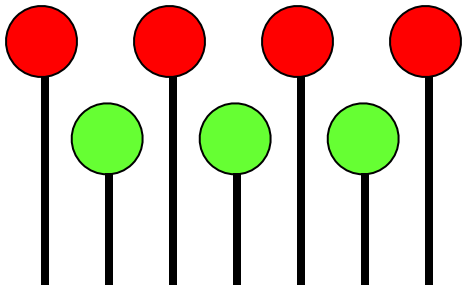
Time

Multiple Discrete States

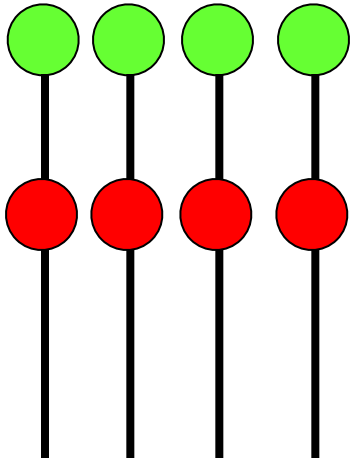
- Easier multi-bit storage due to discrete states
- Discreteness reduces variability

Admixtures

- Different molecules can be mixed in same chip
- Although hybrid technologies not new:
  - Nanotechnology offers new twist
  - Different molecules can occupy same physical space

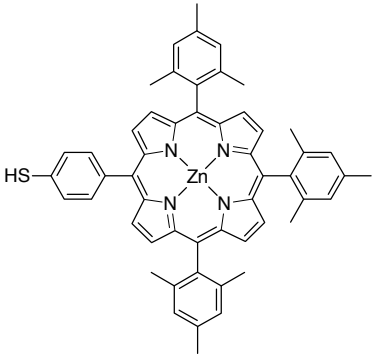


admixture

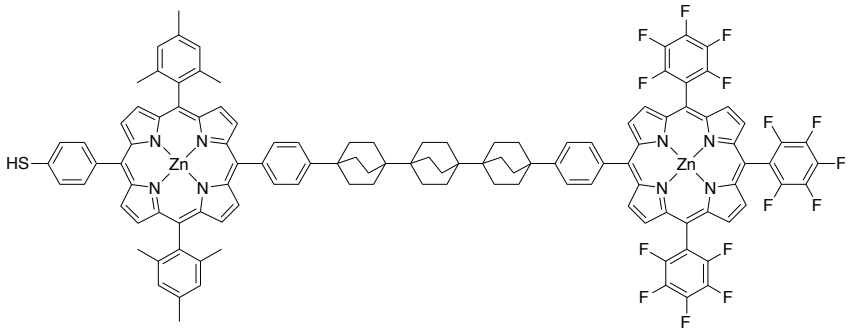


bipartite

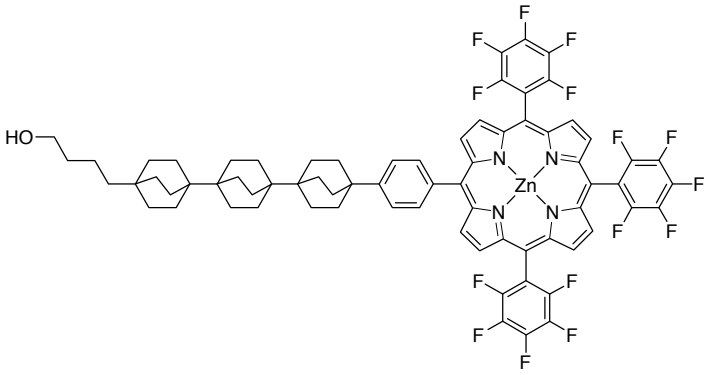
Dual Molecules



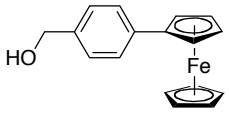
primary storage molecule



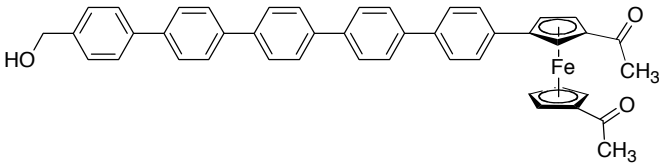
primary storage molecule *secondary storage molecule*



secondary storage molecule



primary storage molecule



secondary storage molecule

E. Rotenberg and J. Lindsey.
Variable-Persistence Molecular Memory Devices and Methods of Operation Thereof. US Patent #6,944,047.

Possibilities

- Unusual memory hierarchy
  - Memories with different attributes (speed, power, volatility) cohabit same space
  - New challenges and opportunities for optimizing data "placement" for power and performance
- Admixtures enable different business models
  - Ship product with multiple molecules but only one configured
  - Multiple virtual products in one physical product

The State of ZettaRAM

- Contribution
  - Consolidated and distilled papers and patents
  - Unified discussion of core technology, embodiments, key properties, and implications
- ZettaRAM has signs of disruptive technology
  - Cheap fabrication of high perf. memory (by all metrics)
  - Practical mixed logic/DRAM
  - Practical 3D memory
  - Exceeds DRAM power scaling limits
  - Intelligent power management
  - Efficient multi-bit storage
  - Memory hierarchies cohabiting same space
  - Multiple virtual products in one physical product