

The State of ZettaRAM

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Goal of Talk

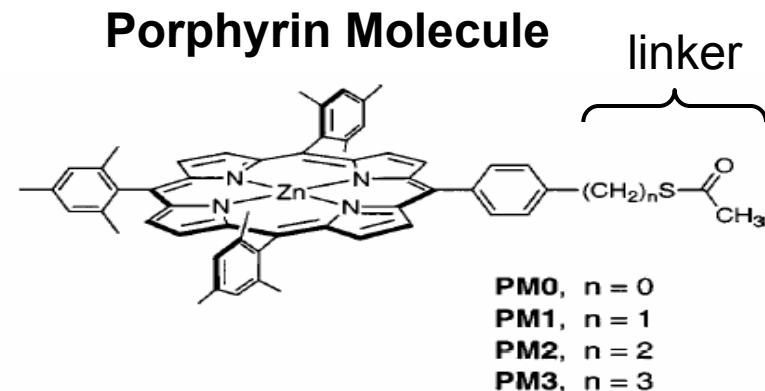
- High level (casual) talk about ZettaRAM
- Consolidate papers and patents
 - Core technology
 - Three different embodiments
 - Key novel properties
 - Implications

Core Technology

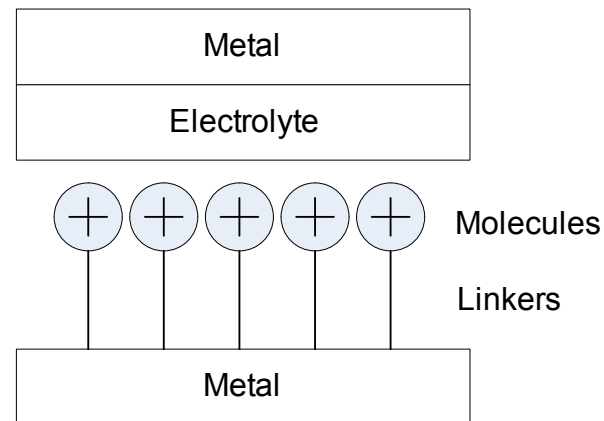
- New memory from ZettaCore
 - Genesis in DARPA Moletronics
 - Molecule stores 1 charge (0, +1)
 - Some molecule types store multiple charges (0, +1, +2)

- Long term
 - 1 molecule = 1 bit

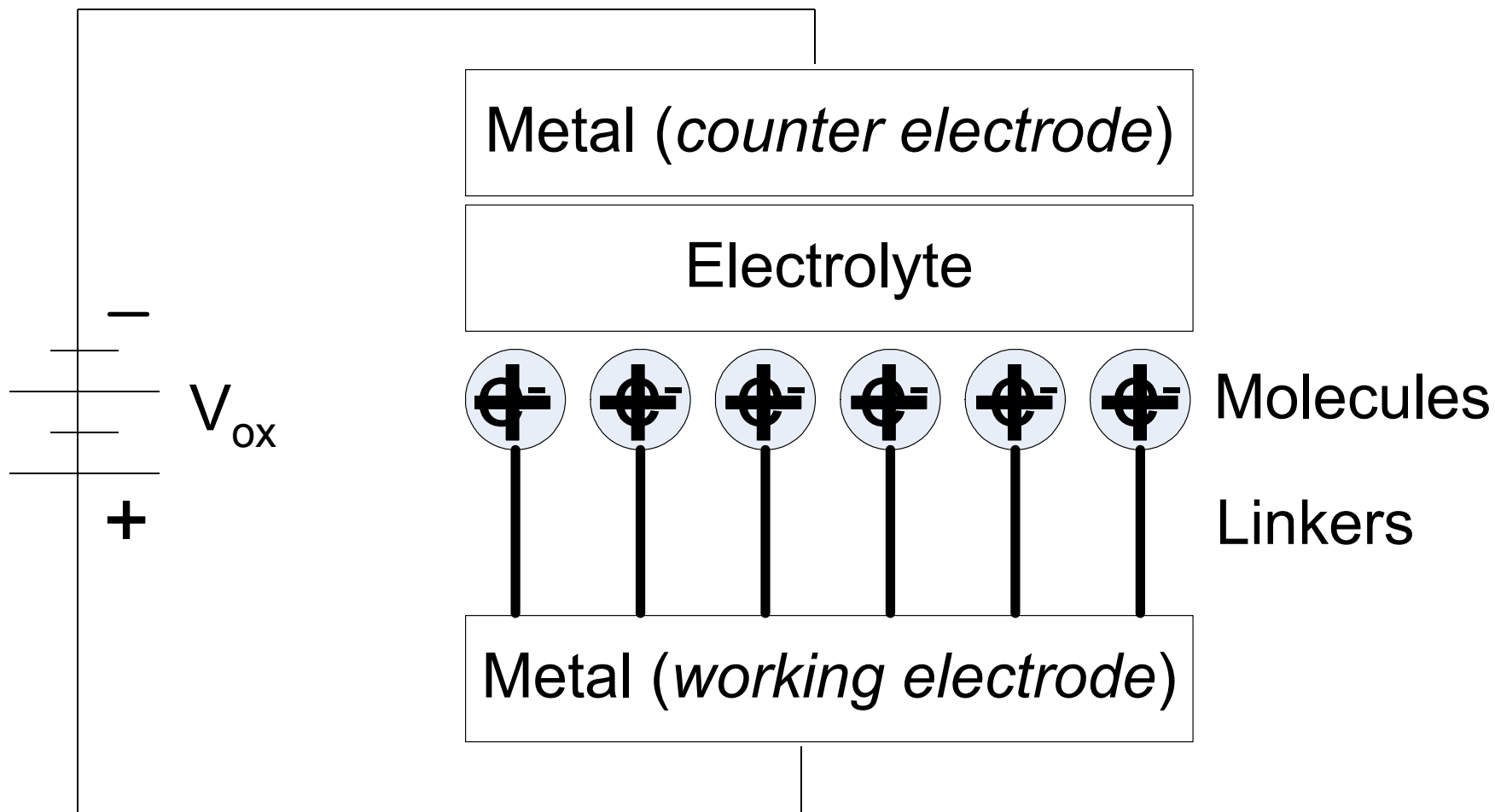
- Near term
 - Use molecules in aggregate
 - Molecular capacitor



ZettaRAM Molecular Capacitor



Molecular Capacitor



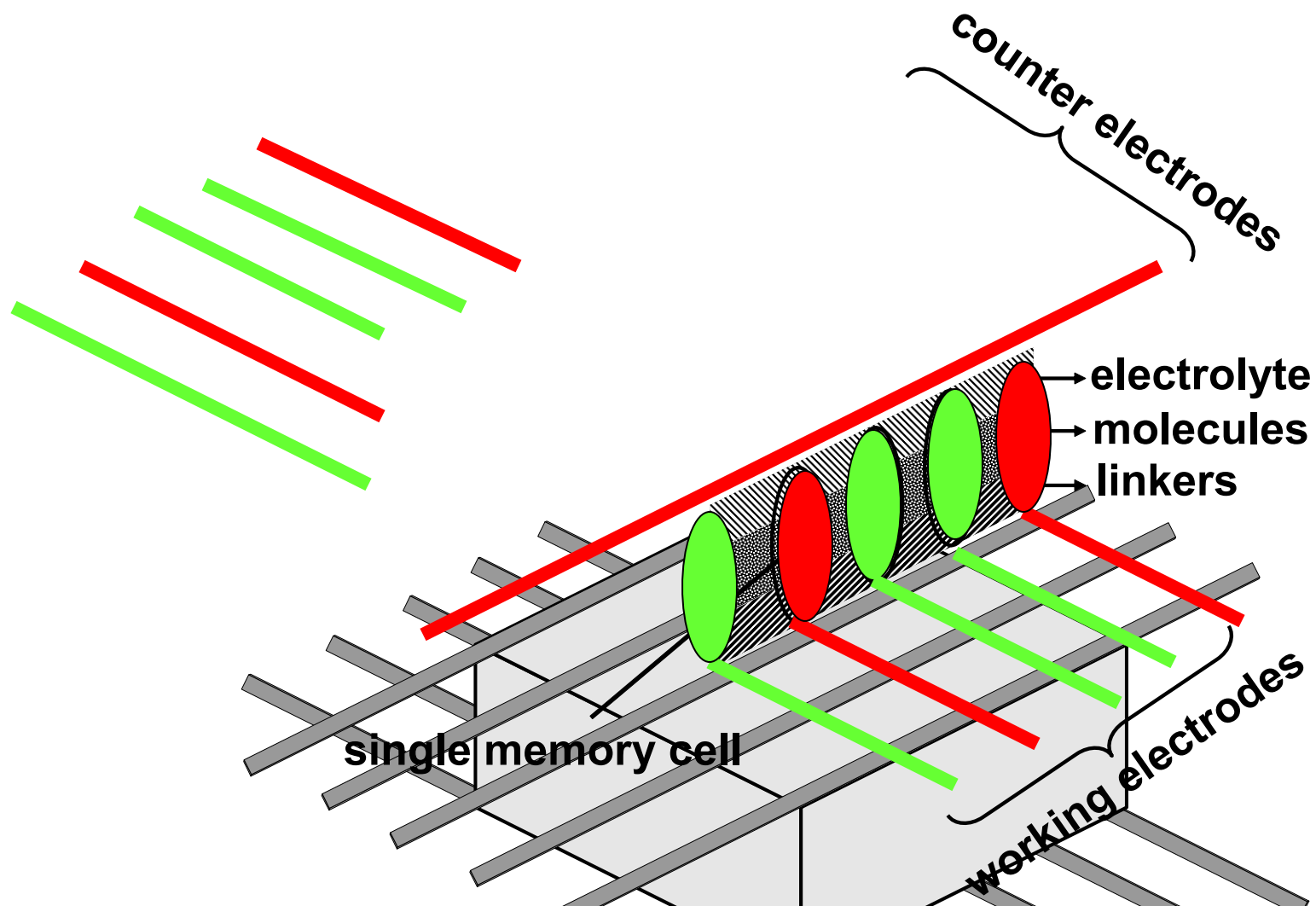
Linker & Electrolyte

- 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



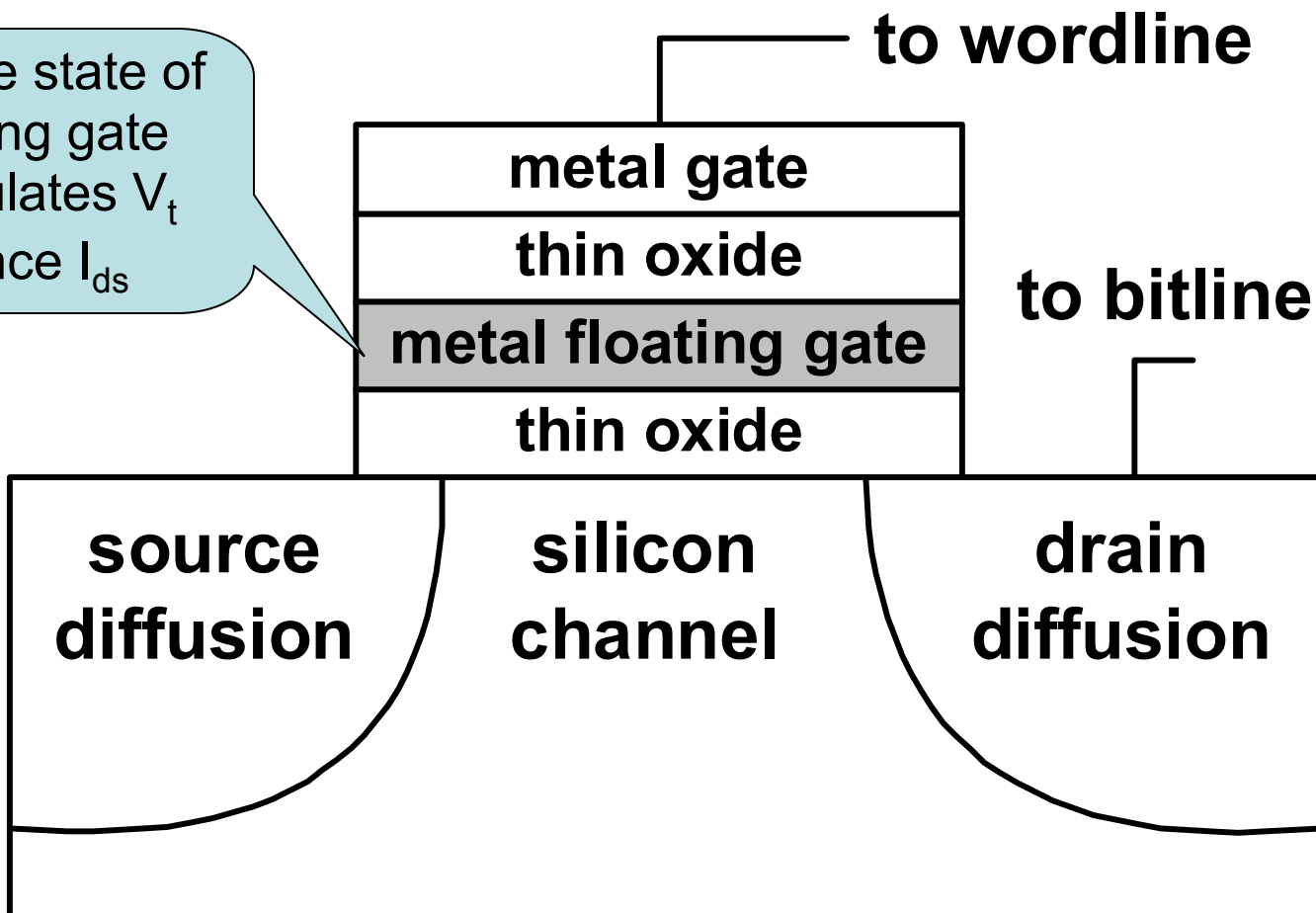
Crossbar Features

- 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?

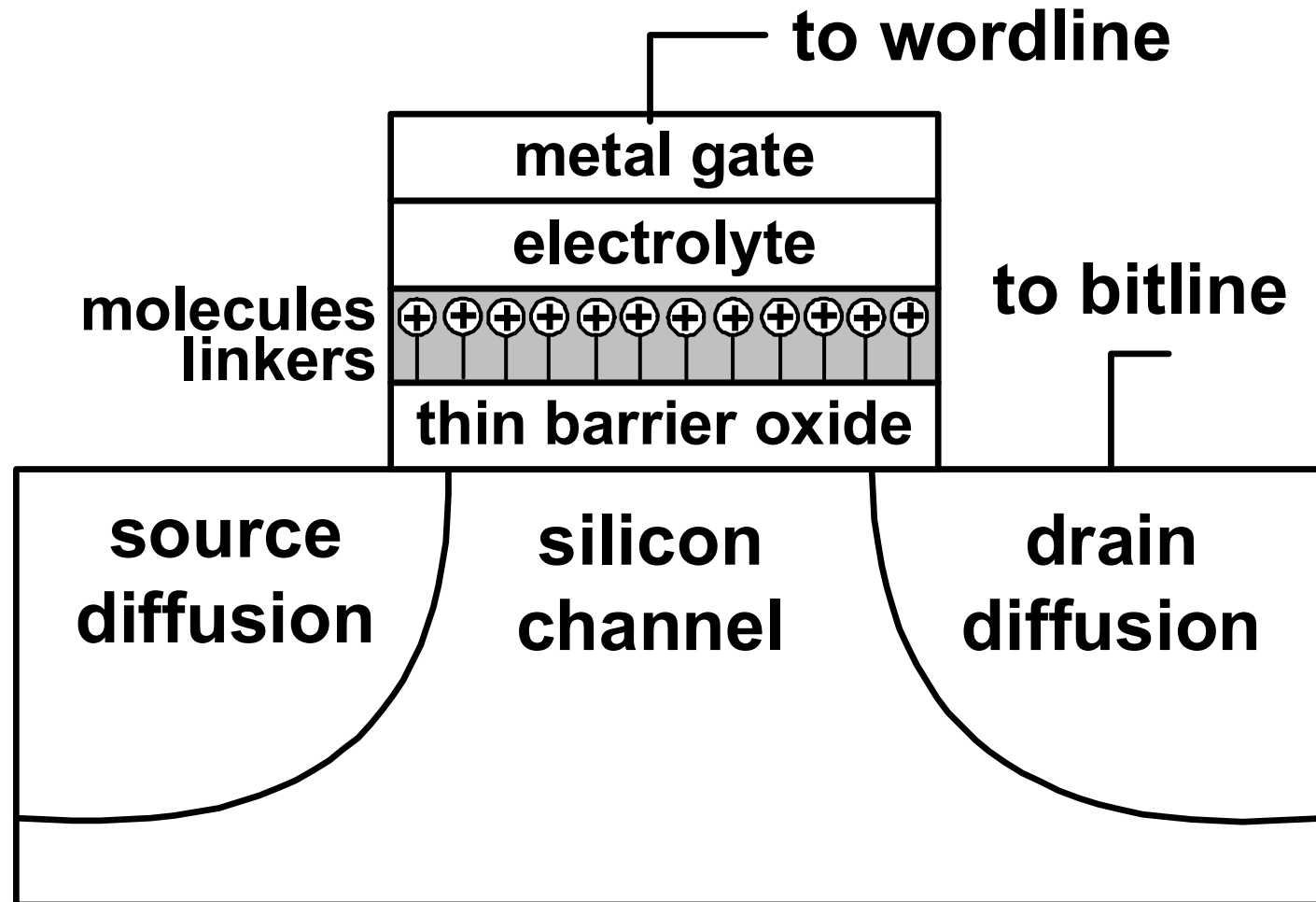
Crossbar Fate

- 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

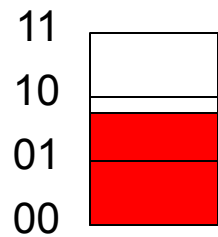


MoleFET Flash Memory

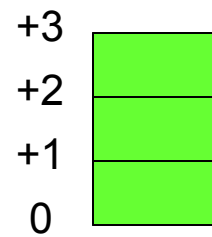


MoleFET Features

- 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

$$V_{\text{prog}} > V_{\text{ox3}}$$

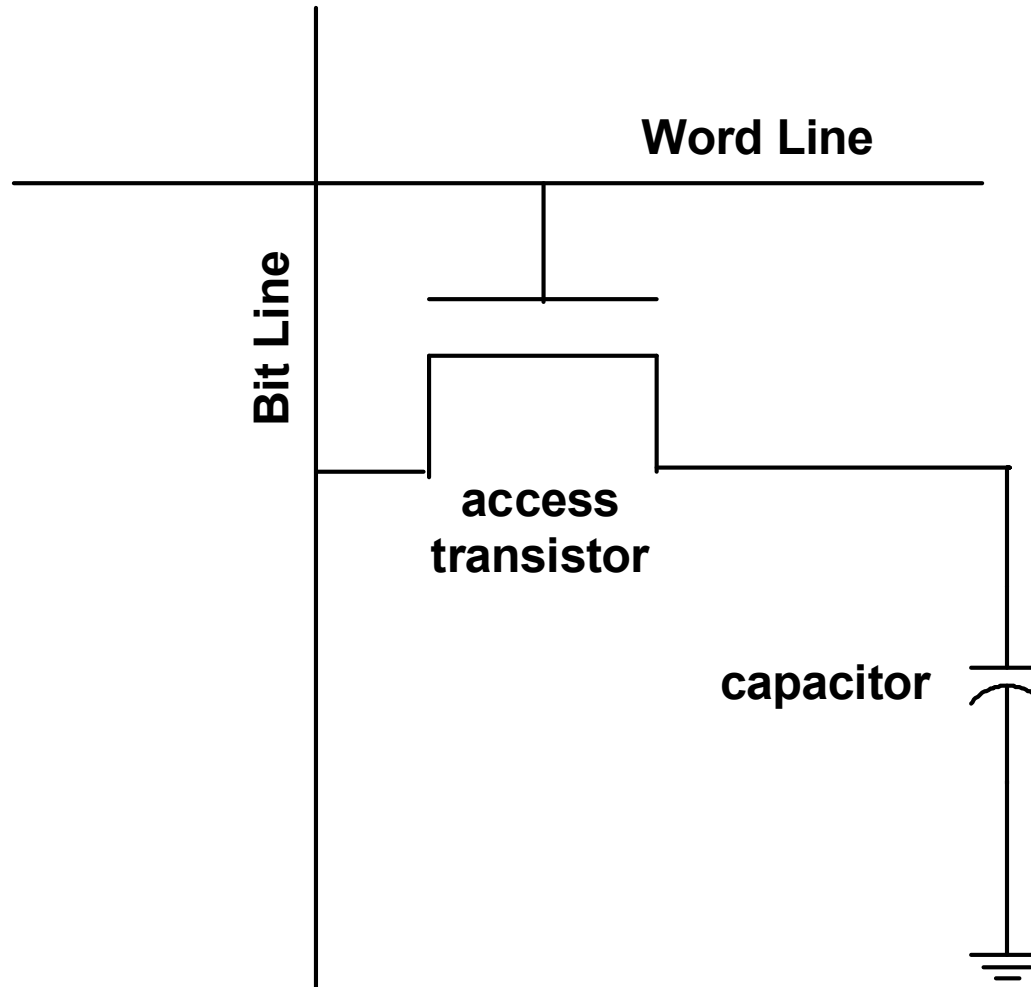
$$V_{\text{prog}} > V_{\text{ox2}}$$

$$V_{\text{prog}} > V_{\text{ox1}}$$

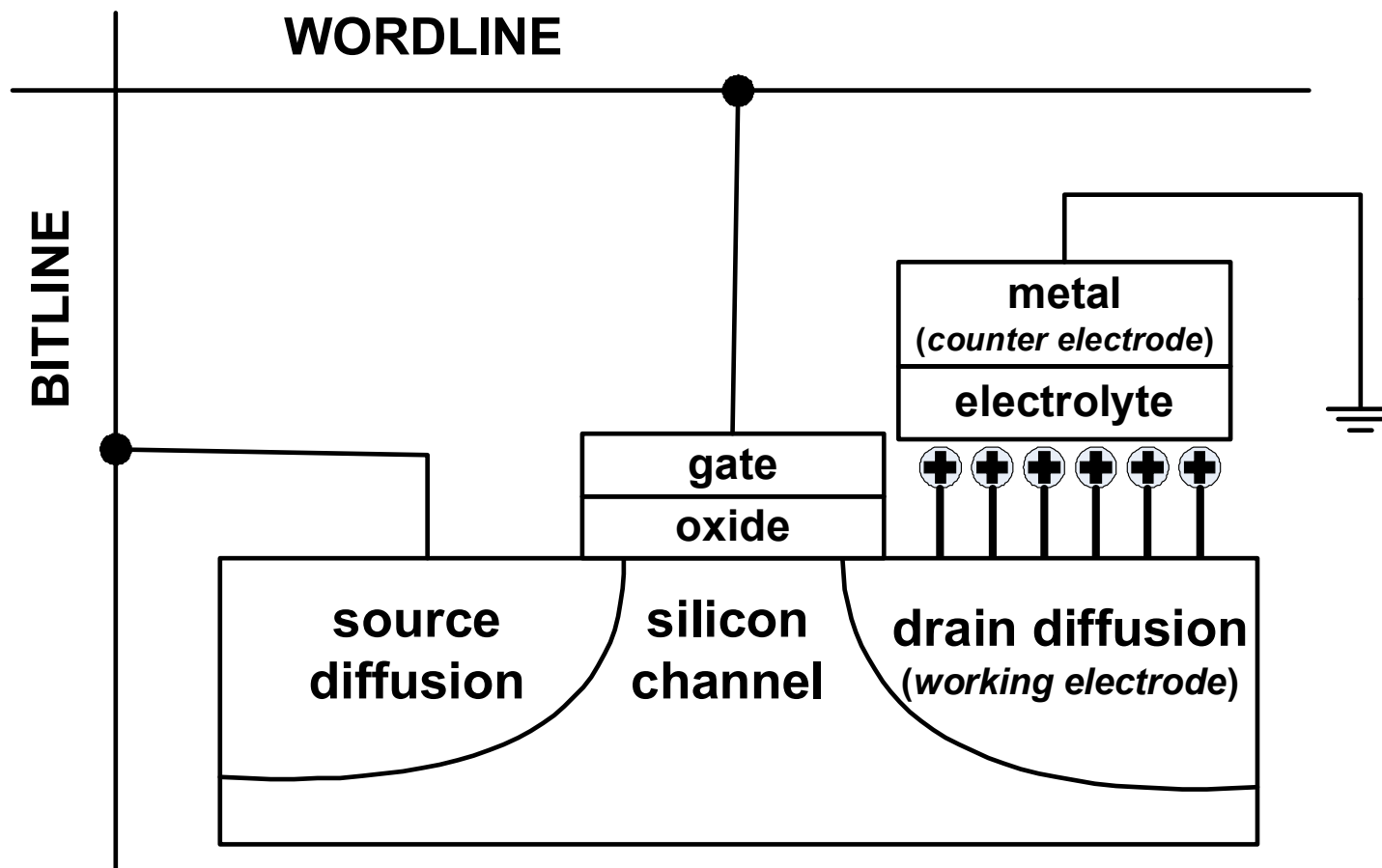
MoleFET Issues

- Striving for larger V_t shift

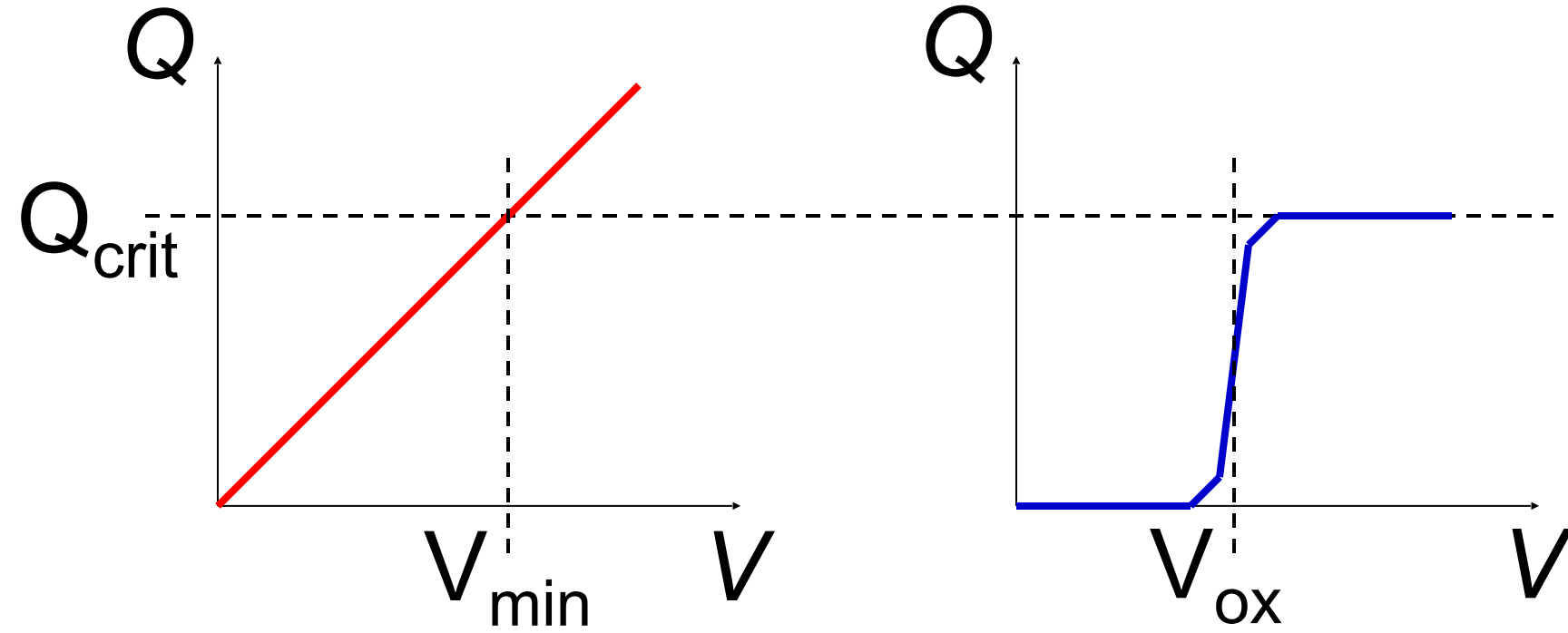
Conventional 1T-1C DRAM Cell



1T-1C DRAM Derivative



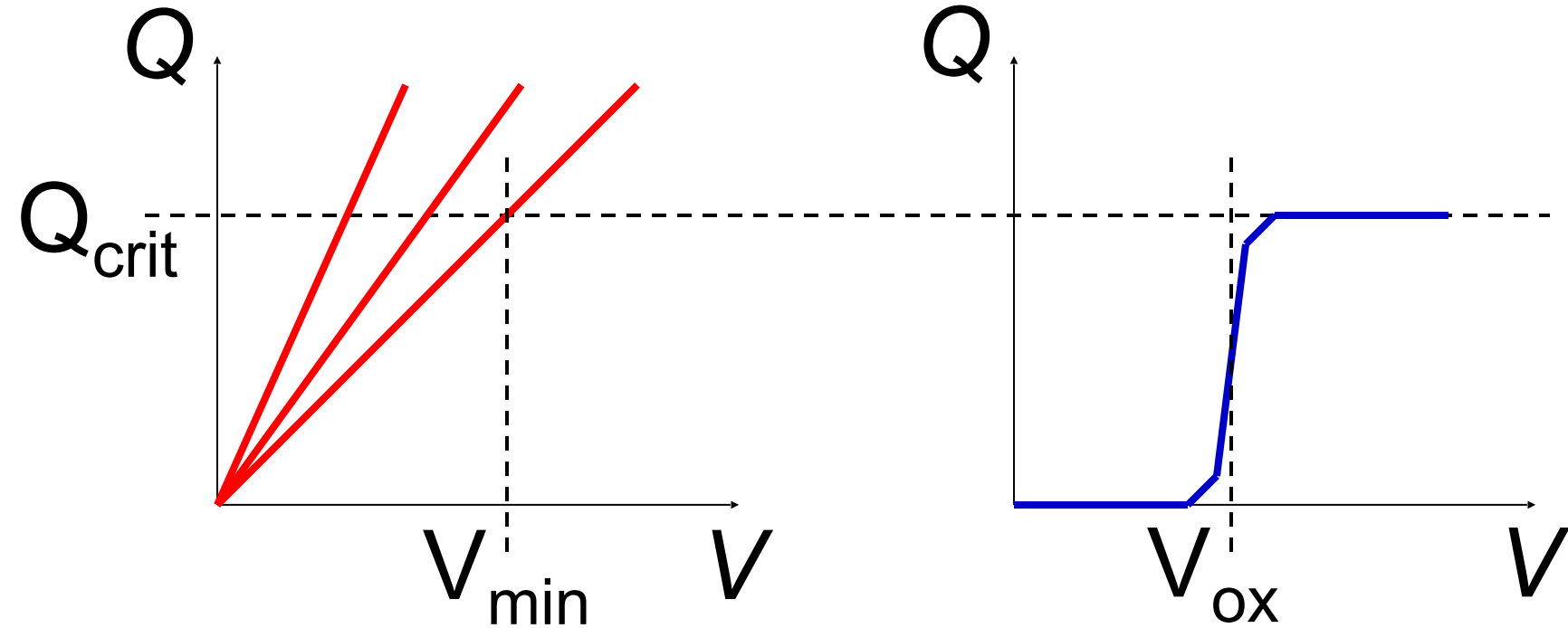
DRAM Voltage Scaling Limits



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

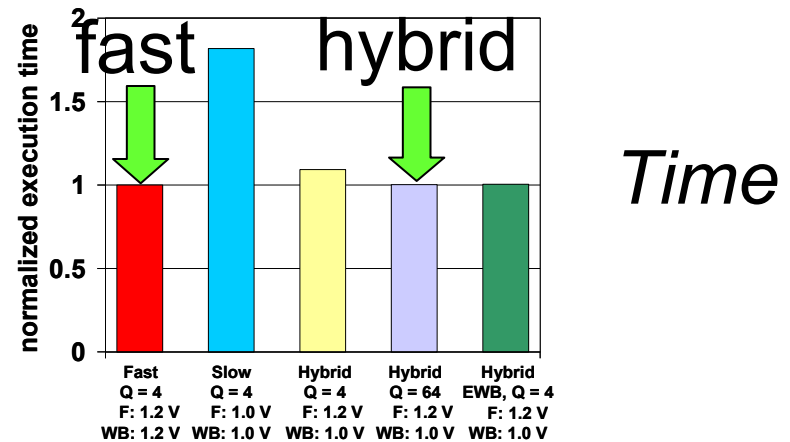
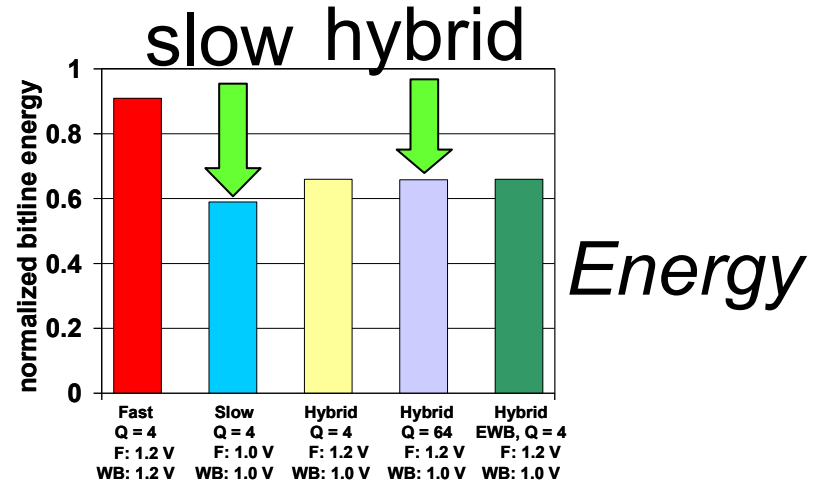
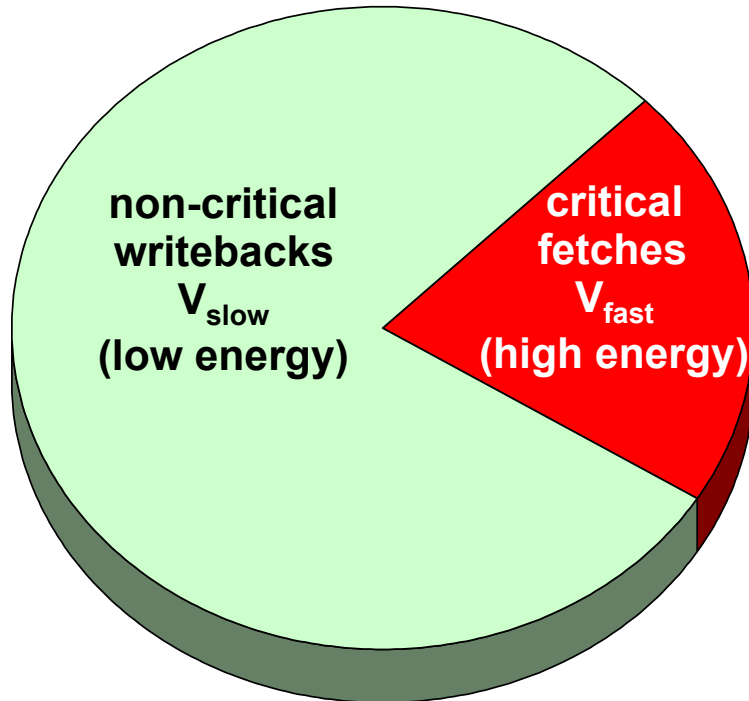
- Fixed charge independent of voltage
- Charge does not constrain voltage
- Power-scalable DRAM derivative extends roadmap of this important memory technology

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

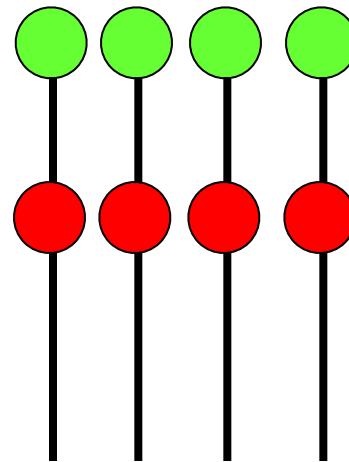
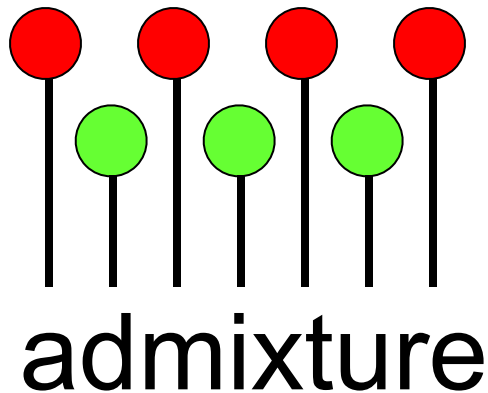


Multiple Discrete States

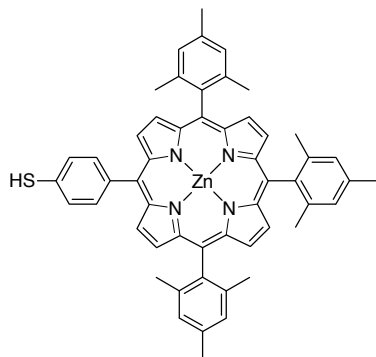
- Easier multi-bit storage due to discrete states
- Discreteness reduces variability

Admixtures

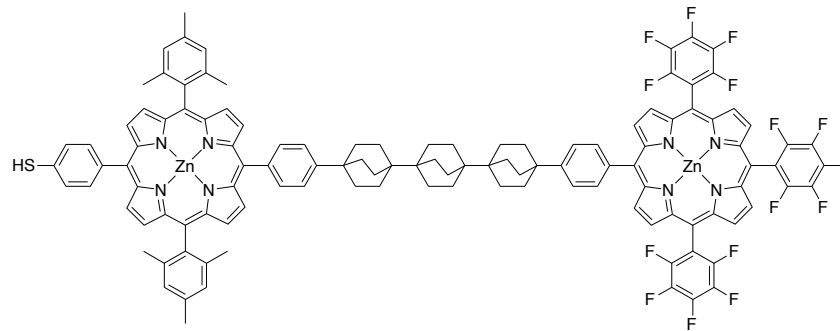
- Different molecules can be mixed in same chip
- Although hybrid technologies not new:
 - Nanotechnology offers new twist
 - Different molecules can occupy same physical space



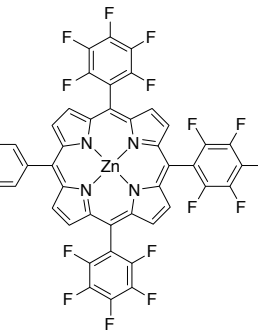
Dual Molecules



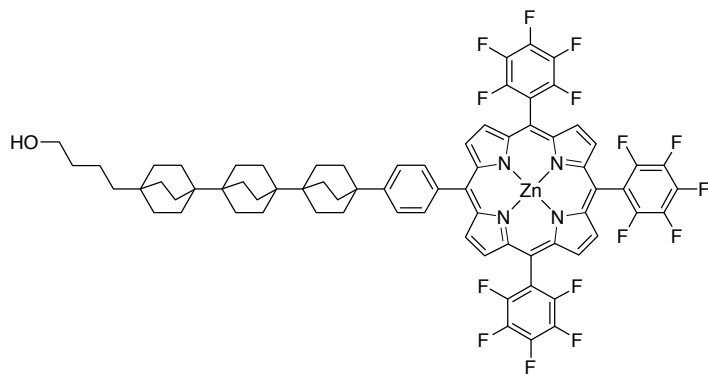
primary storage molecule



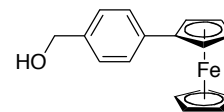
primary storage molecule



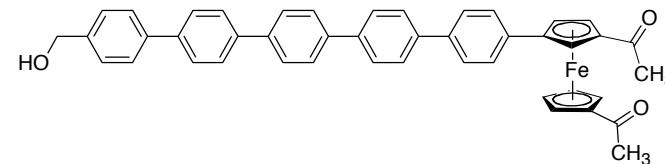
secondary storage molecule



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