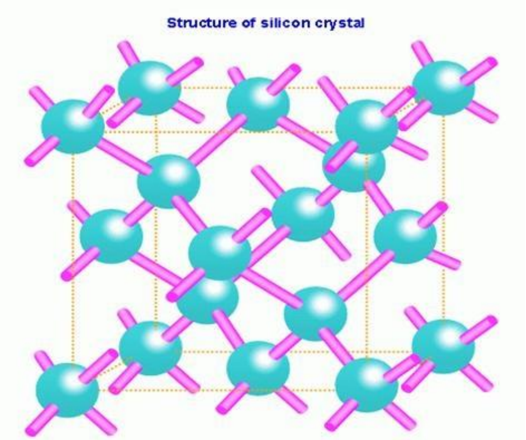

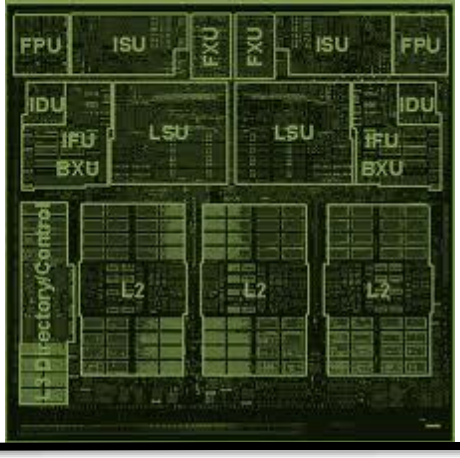

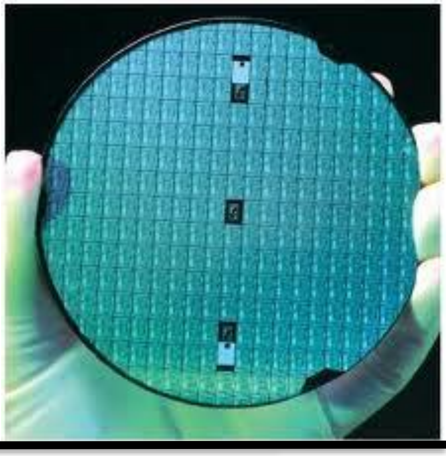

ECE 225

VLSI Principles

Lectures 17

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Memory Classification

- Size
- Timing Parameters
- Function
- Access Pattern

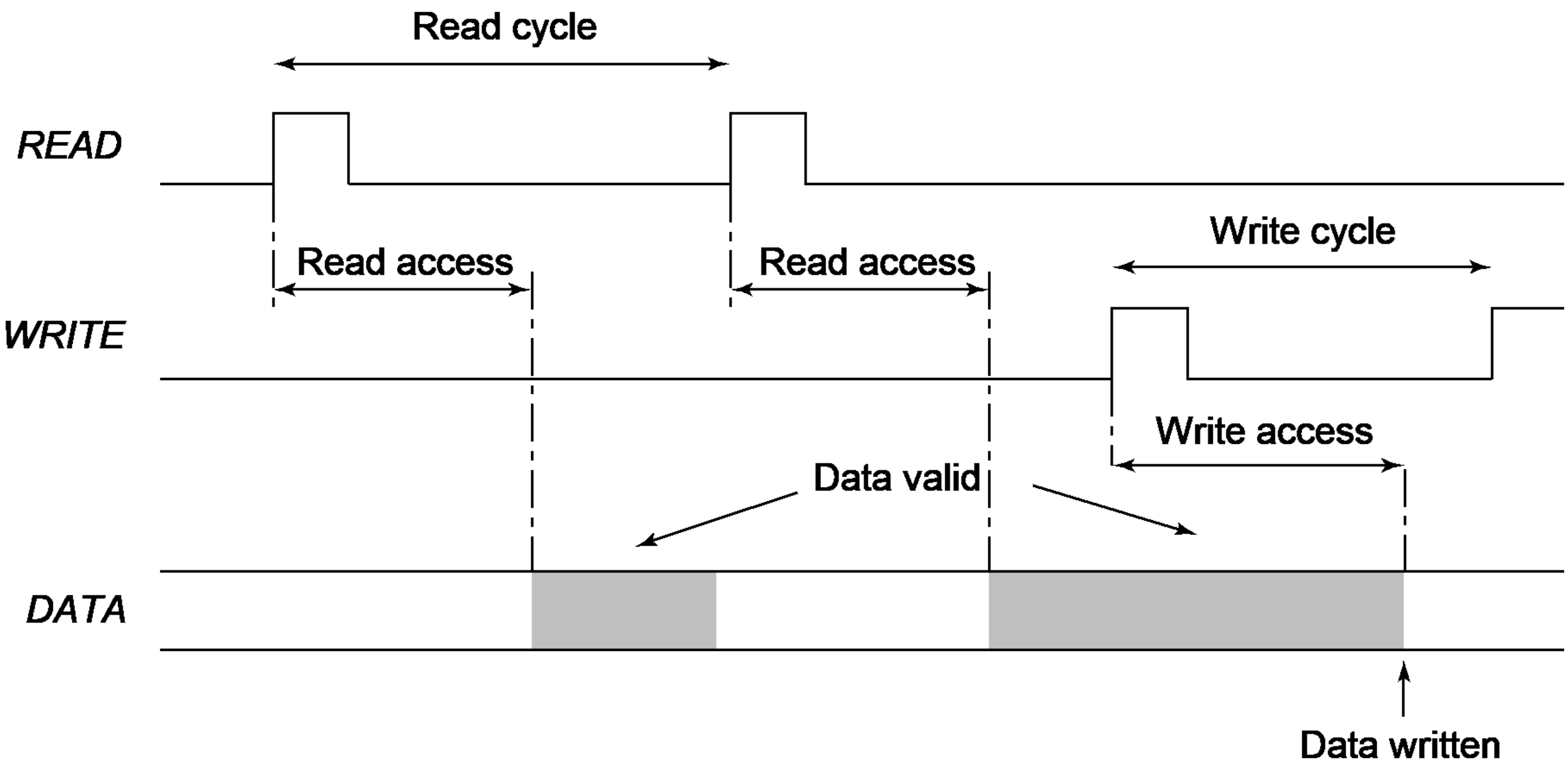
Memory Size

- Depends on the level of abstraction
- **Bits**: (used by circuit designers) are equivalent to the number of individual cells (FFs or Registers) to store data
- **Bytes**: (used by chip designers) are groups of 8 or 9 bits or their multiples: Kbyte, Mbyte, Gbyte, Tbyte
- **Words**: (used by system designers) represent a basic computational entity. For example, a group of 32 bits represent a word in a computer that operates on 32 bit data

Timing Parameters

- **READ-Access Time**: time it takes to retrieve (read) from the memory. This is equal to the delay between the read request and the moment the data becomes available at the O/P.
- **WRITE-Access Time**: time elapsed between a write request and the final writing of the input data into the memory
- **CYCLE Time**: minimum time required between successive reads or writes

Memory Timing: Definitions



Note: Read and Write cycles do not necessarily have the same length but are considered to be equal for simplicity of system design.

Function

- **Read-Only Memory (ROM)**:
  - encode the information into the circuit topology-by removing or adding transistors. The topology is hard wired and the data cannot be modified….can only be read.
  - They belong to the class of **Non-volatile** memories. Disconnection of the supply voltage does not result in a loss of the stored data.
- **Read-Write Memories (RWM)**: called as **RAM** (Random-Access Memories).
  - **Static** (retains data if Vdd is retained): example SRAM
  - **Dynamic** (needs periodic refreshing): example DRAM
  - They use active circuitry to store information and belong to the class of **Volatile** memories.

Function….cont'd

- **Non-Volatile Read-Write (NVRWM)**:
  - Recent Non-Volatile Memories can read and write----although write function is substantially slower
  - Novel, cheap and dense: Fastest growing among semiconductor memories
- Examples:
  - EPROM: Electrically Programmable ROM
  - E^2PROM: Electrically Erasable and Programmable ROM
  - Flash memory

Access Pattern

- **Random-Access (RAM):**
  - memory locations can be read or written in a random manner
  - Most ROMs and NVRWMs allow random access….but "RAM" is used for the RWMs only
- **Serial Access:**
  - Restricts the order of access. Results in faster access times, smaller area, or allows special functionality
  - Examples: (Video Memories)
    - FIFO (first-in first-out)
    - LIFO (last-in first-out)
    - Shift Register
- **Content-Addressable Memory (CAM):** (non-random access)
  - Also known as associative memory
  - Doesn't use an address to locate the data…..rather uses a word of data itself as input… when input data matches a data word stored in memory array, a MATCH flag is raised
  - Important component of the cache architecture of most microprocessors

Semiconductor Memory Classification

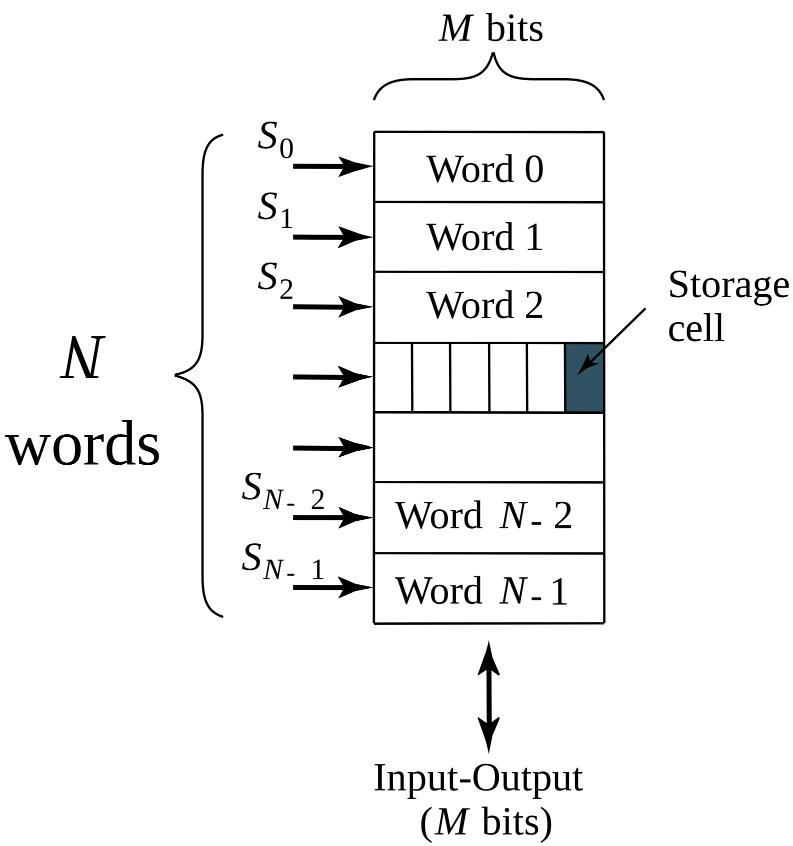
Read-Write Memory		Non-Volatile Read-Write Memory	Read-Only Memory
Random Access	**Non-Random Access**	EPROM	Mask-Programmed
SRAM	FIFO	E^2PROM	Programmable (PROM)
DRAM	LIFO	FLASH	
	Shift Register		
	CAM		

Where does your brain's memory fit into these classification schemes?

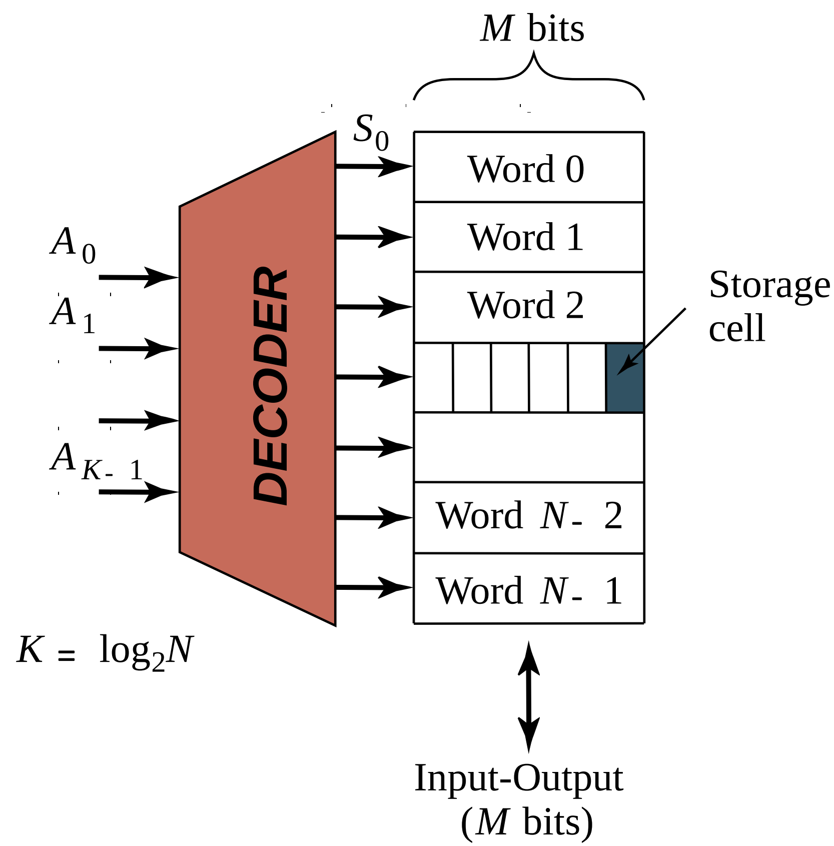
More Classification

- **I/O Architecture:**
  - Based on the number of data input and output ports
  - Most memories use a single I/O port
  - **Multiport memories** offer higher bandwidth
    - Example: register files used in RISC processors
    - Adds more complexity to the design
- **Application:**
  - Embedded Memories in SoCs
  - For massive storage (multiples of Tbytes and beyond), more cost effective solutions are to use **magnetic tapes** and **optical disks-**--they however, tend to be slower and provide limited access pattern

Memory Architecture: Decoders



Intuitive architecture for N x M memory
Too many select signals:
N words == N select signals

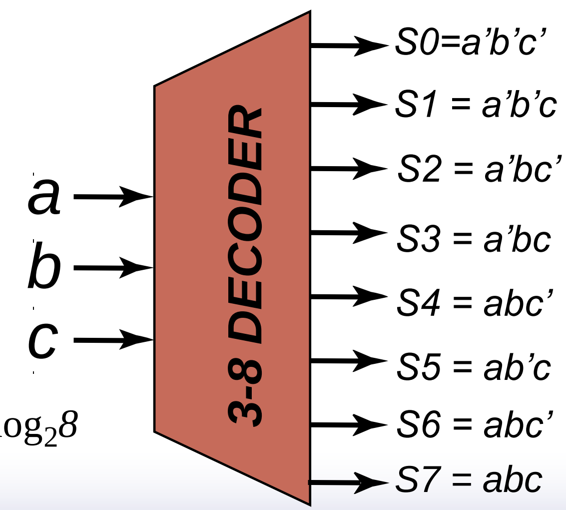


Decoder reduces the number of select signals

$K = \log_2 N$

Decoder Basic

- Recall that a decoder is a combinational circuit with k inputs and at most 2^k outputs.
- Its characteristics property is that for every combination of input values only ONE output =1 at the same time.
- Used to route input data to specific output line.



$3 = \log_2 8$

For example: for a=b=c=0, only S0 =1

Read-Write Memories (RAM)

- **STATIC (SRAM)**

  Data stored as long as supply is applied
  Large (6 transistors/cell)
  Fast
  Differential

- **DYNAMIC (DRAM)**

  Periodic refresh required
  Small (1-3 transistors/cell)
  Slower
  Single Ended

6-transistor CMOS SRAM Cell

Should be minimum sized to achieve high memory density…..

READ Operation:

Assume 1 is stored at Q

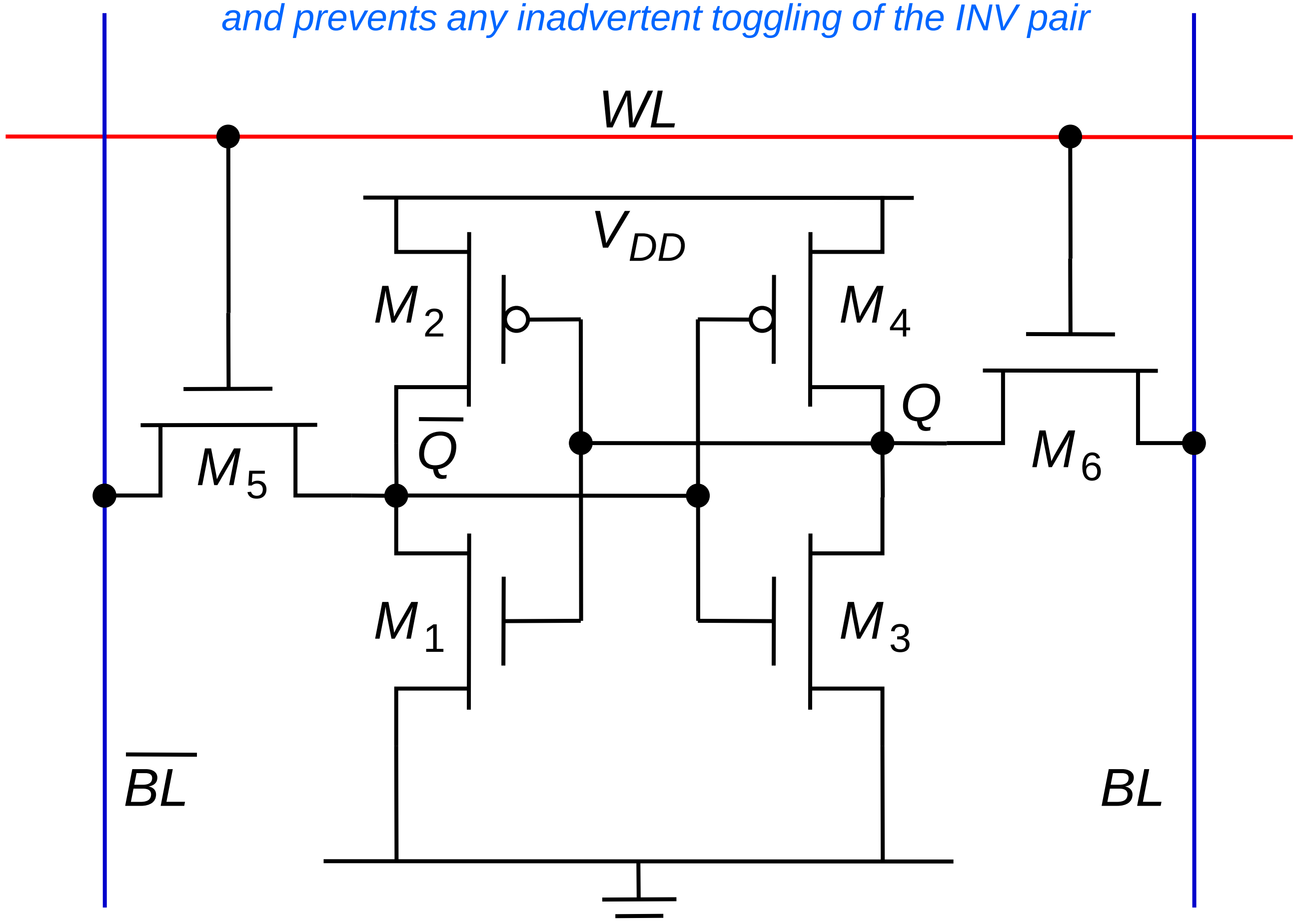
Assume both BLs are held high before the read.

Read cycle started by asserting the WL, enables PTs M5 and M6

During a correct read operation values stored in Q and $\overline{Q}$ are transferred to the bit lines leaving BL at its precharge value and by discharging $\overline{BL}$ through M1-M5

A "0" can be read in a similar manner (now BL gets discharged through M6 and M3)

Major advantage of dual BL: Q is clamped to Vdd by BL and prevents any inadvertent toggling of the INV pair



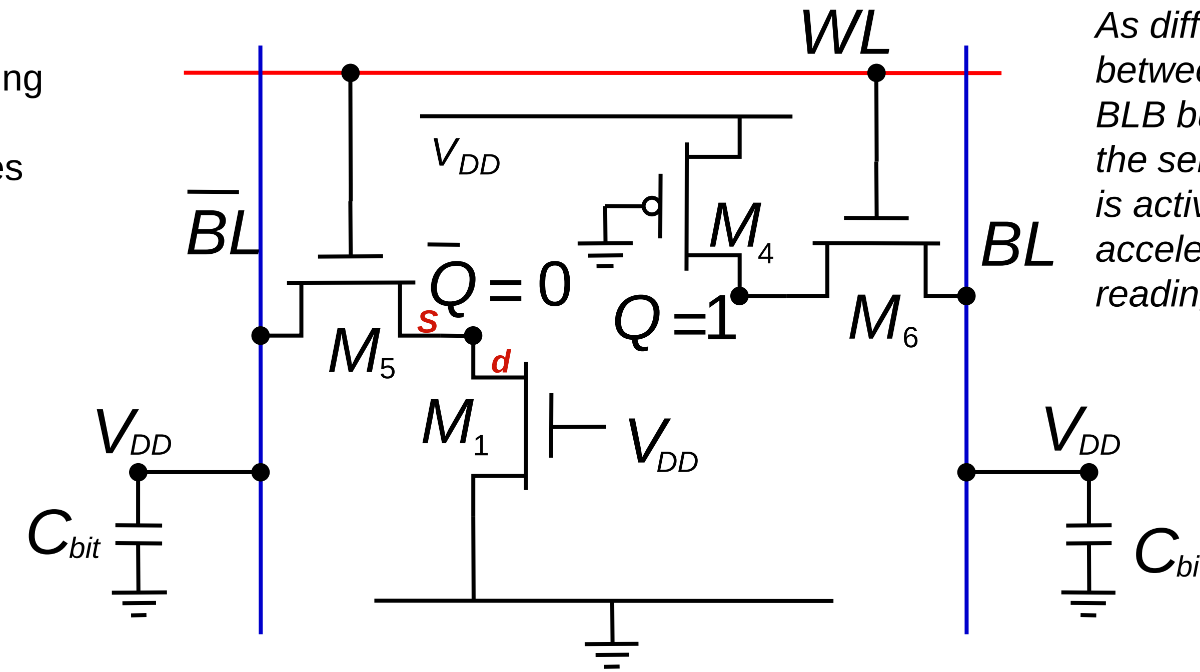
SRAM cell should be as small as possible…..but reliable operation requires careful sizing…

CMOS SRAM Analysis (Read "1" operation)

Transistor sizing is needed to avoid writing 1 accidentally, i.e., voltage at $\overline{Q}$ becomes > V_M of Inv M3-M4

M1 must be stronger than M5

$\overline{Q}$ must stay low enough so that there is no substantial current through M3-M4 INV



As difference between BL and BLB builds up, the sense amp. is activated to accelerate the reading process

$$k_{n,M5}\left((V_{DD} - \Delta V - V_{Tn})V_{DSATn} - \frac{V_{DSATn}^2}{2}\right) = k_{n,M1}\left((V_{DD} - V_{Tn})\Delta V - \frac{\Delta V^2}{2}\right)$$

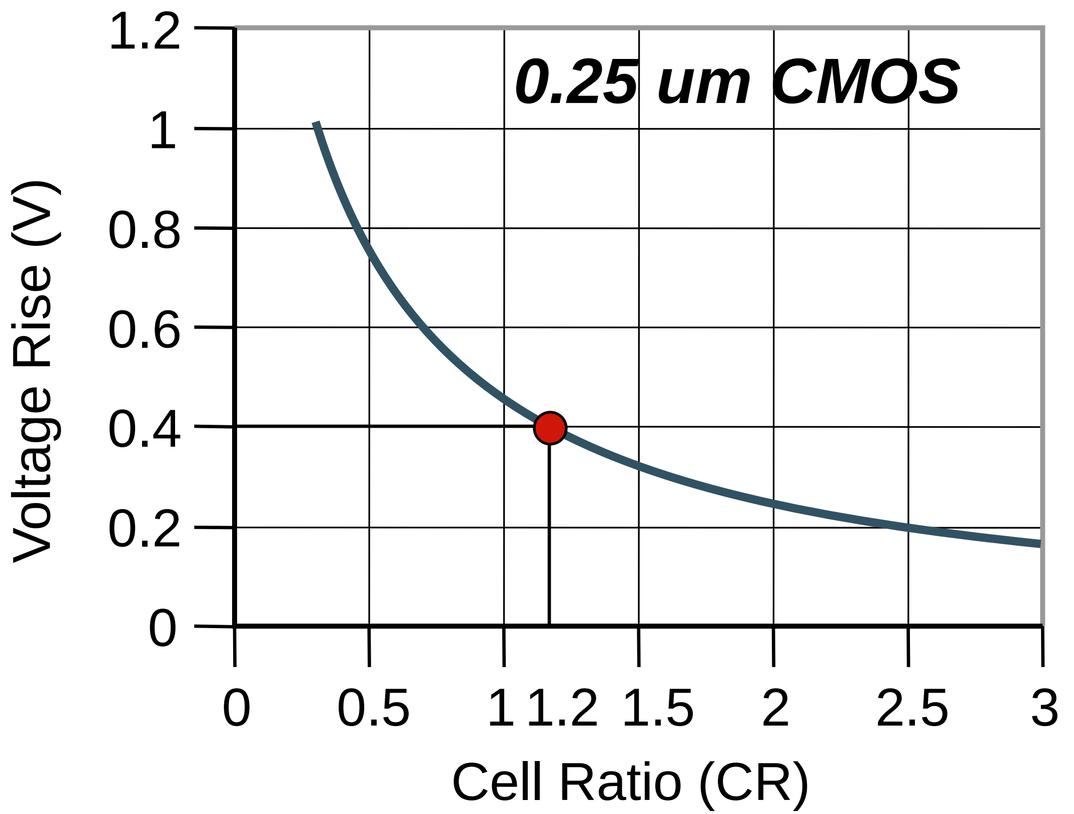
(M5 in saturation) (M1 in linear)

$$\Delta V = \frac{V_{DSATn} + CR(V_{DD} - V_{Tn}) - \sqrt{V_{DSATn}^2(1 + CR) + CR^2(V_{DD} - V_{Tn})^2}}{CR}$$

Value of the ripple voltage

CR = cell ratio = M1/M5

CMOS SRAM Analysis (Read)



$$CR = \frac{W_1/L_1}{W_5/L_5}$$

Choose M5 to be minimum size and M1 > M5

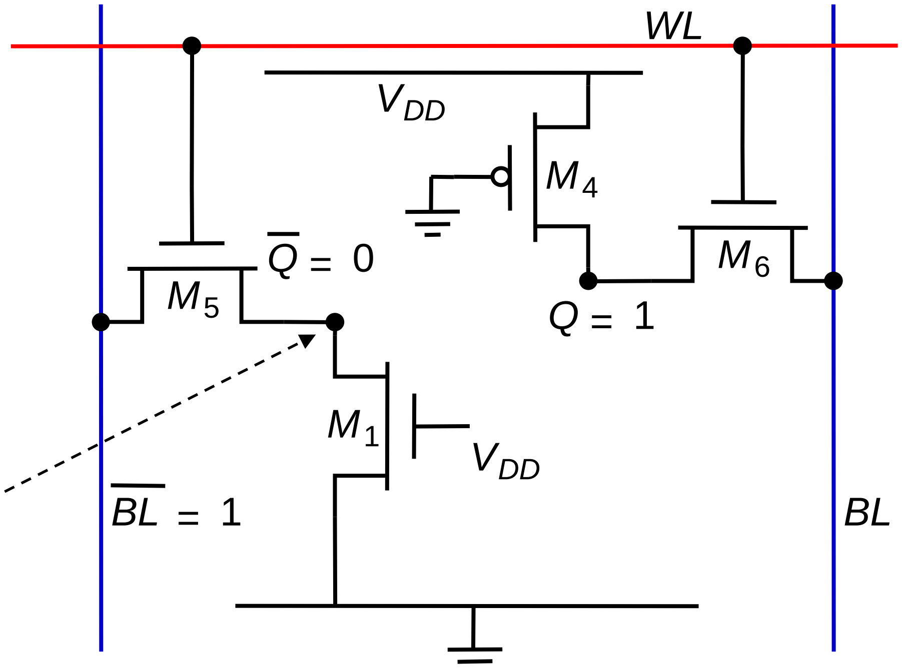
Node voltage must stay below the Vth of M3: CR must be >1.2

CMOS SRAM Analysis (Write)

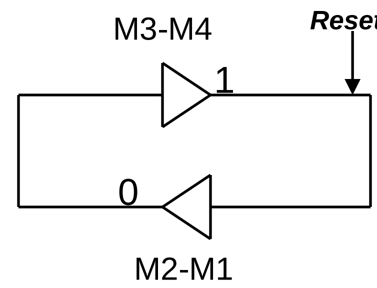
Assume that Q=1

To write a 0 in the cell: set $\overline{BL}$=1 and BL=0

Similar to applying a reset pulse to an SR latch. FF will change state if sized properly



$\overline{Q}$ cannot be pulled high due to the sizing of M5 and M1 already done for reading



Reliable writing of the cell is ensured if we can pull node Q low enough—below the Vth of M1

New value must be written through M6

$$k_{n,M6}\left((V_{DD}-V_{Tn})V_Q-\frac{V_Q^2}{2}\right) = k_{p,M4}\left((V_{DD}-|V_{Tp}|)V_{DSATp}-\frac{V_{DSATp}^2}{2}\right)$$

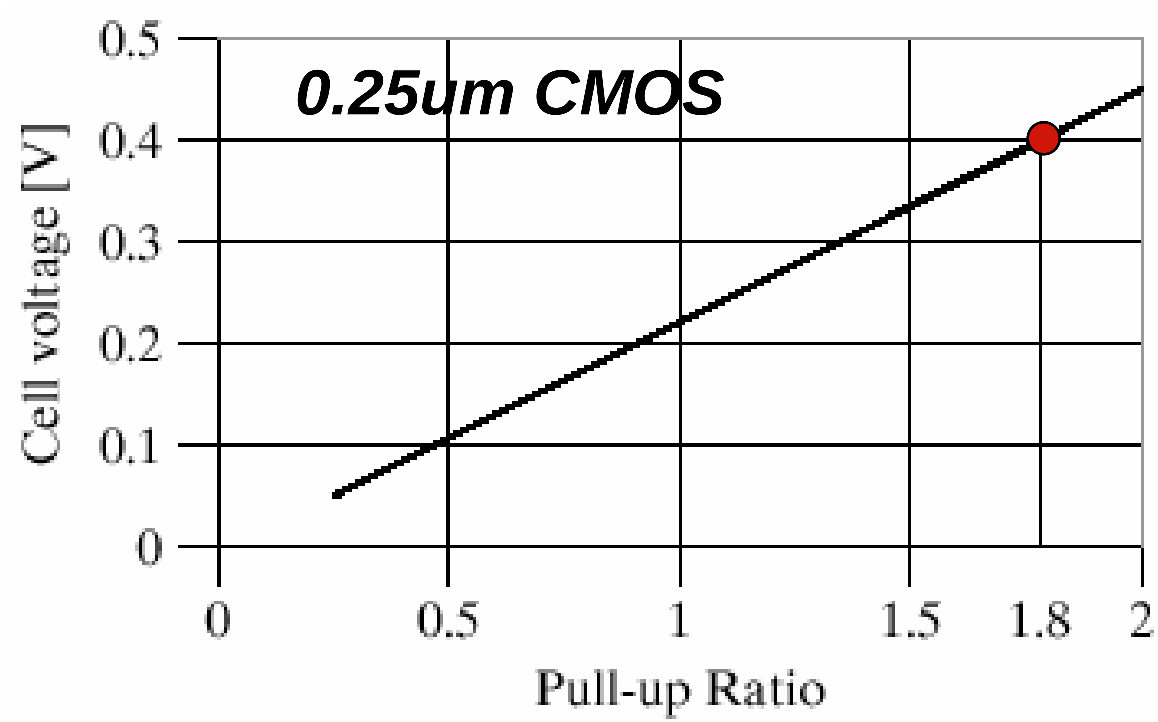
(M6 in linear) *(M4 in saturation)*

$$V_Q = V_{DD}-V_{Tn}-\sqrt{(V_{DD}-V_{Tn})^2-2\frac{\mu_p}{\mu_n}PR\left((V_{DD}-|V_{Tp}|)V_{DSATp}-\frac{V_{DSATp}^2}{2}\right)},$$

PR = pull-up ratio of cell = M4/M6

CMOS SRAM Analysis (Write)

Dependence of V_Q on Pull-up Ratio…..lower PR gives lower V_Q



$$PR = \frac{W_4/L_4}{W_6/L_6}$$

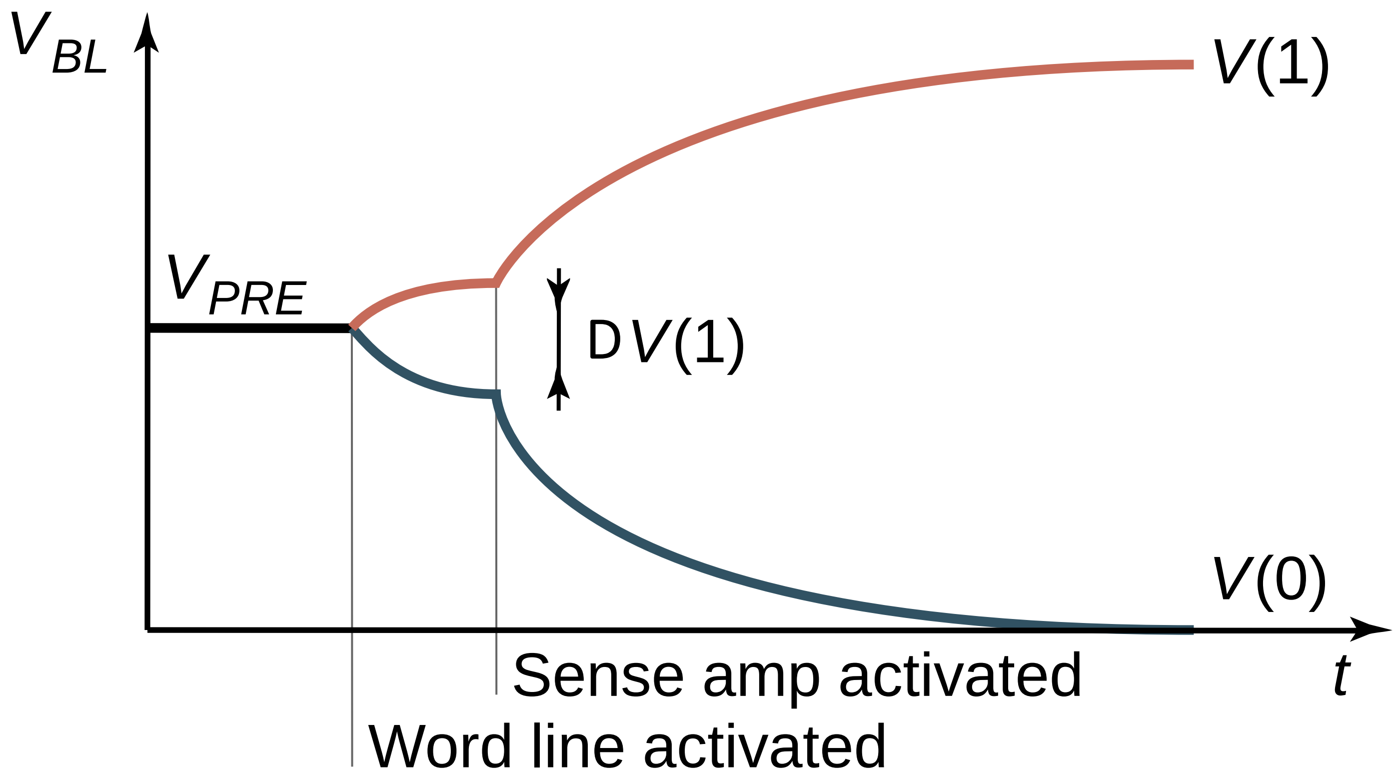
Should be low to keep V_Q low

PR between the PMOS (M4) pull-up and the NMOS (M6) Pass Transistor must be < 1.8 to keep Vtn < 0.4 V

Performance of SRAM

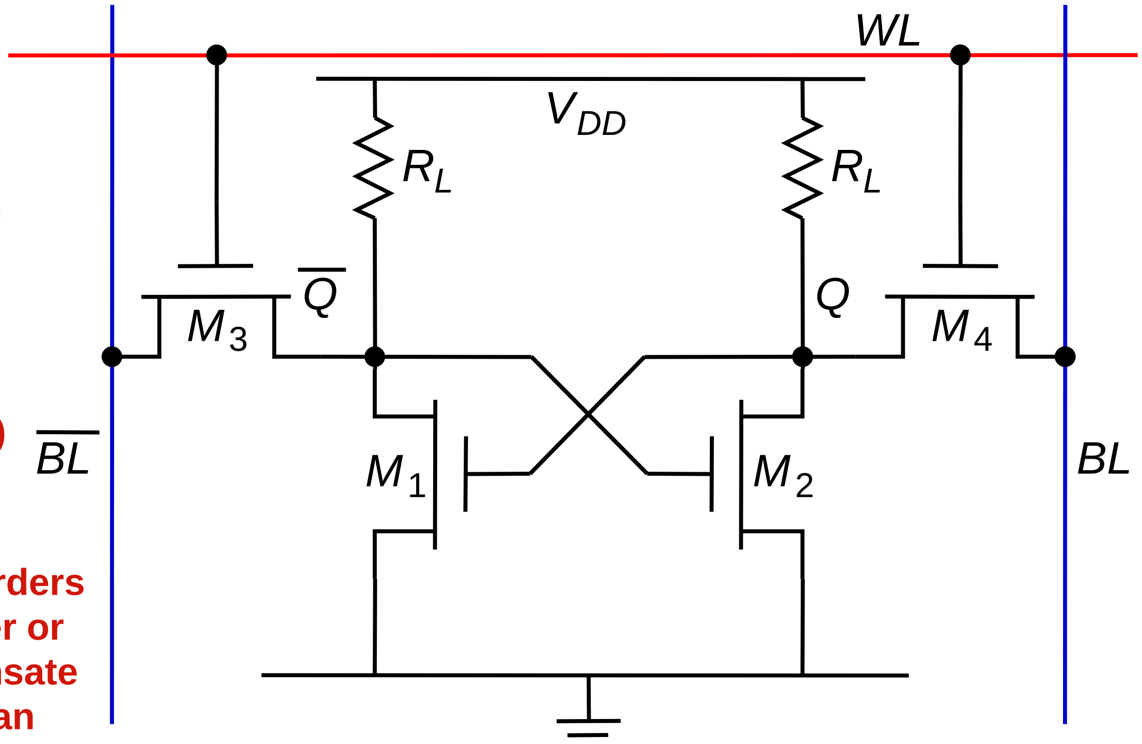
- Read operation is more critical. It requires discharging of the large bit line capacitance through the stack of 2 transistors (M1-M5)
- Write time is dominated by the propagation delay of the cross-coupled inverter pair, since the drivers that set BL and $\overline{BL}$ can be large
- Sense amplifiers used to accelerate Read time….as the difference between BL and $\overline{BL}$ builds up, sense amplifier is activated, and it discharges one of the bit lines

Sense Amp Operation



Resistive-load (4T) SRAM Cell

Reduce area using resistive load inverters…simplifies writing



R_L must maintain the state of the cell, that is compensate for the leakage currents (~10^{-15}A)

I_{load} must be two orders of magnitude larger or > 10^{-13}A to compensate for leakage—puts an upper limit on R_L

Replacing the PMOSs by resistors reduces wiring

SRAM cell size reduced by 1/3

Static power dissipation -- Want R_L large (use undoped poly)
Bit lines precharged to V_{DD} to address t_p problem

SRAM Characteristics

Instead of PMOS devices, use parasitic devices on top of cell structure using thin-film transistors (TFTs)

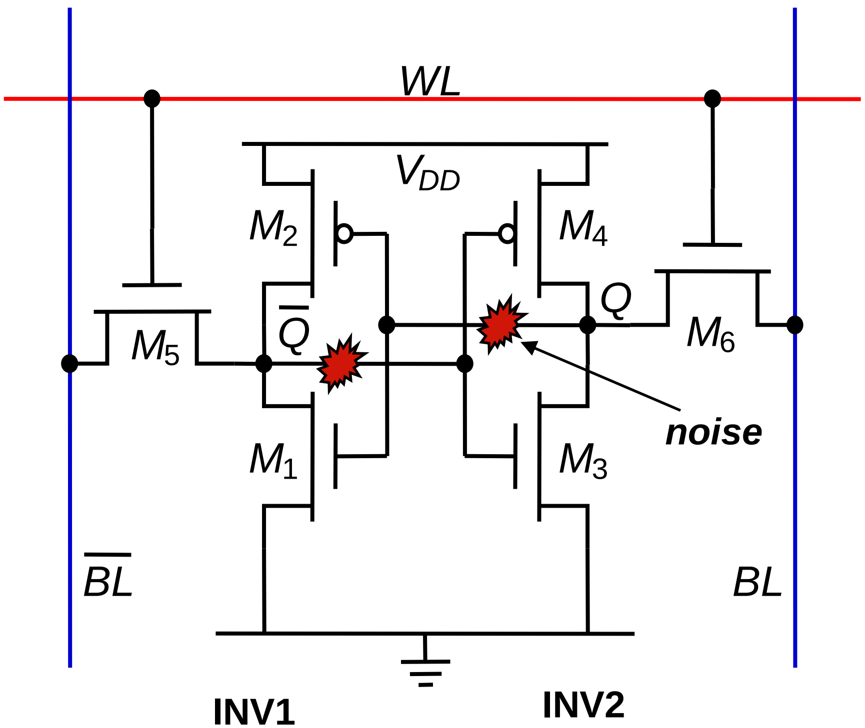
Table 12-2 Comparison of CMOS SRAM cells used in 1-Mbit memory (from [Takada91])

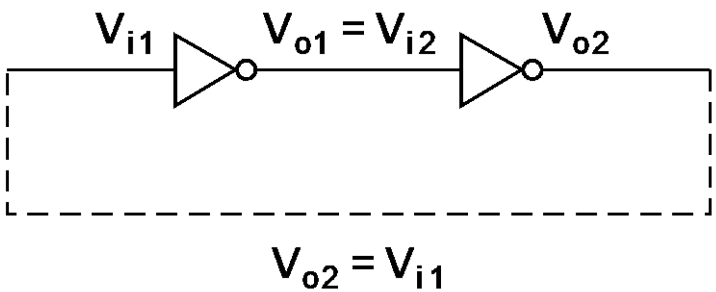
	Complementary CMOS	Resistive Load	TFT Cell
Number of transistors	6	4	4 (+2 TFT)
Cell size	58.2 μm^2 (0.7-μm rule)	40.8 μm^2 (0.7-μm rule)	41.1 μm^2 (0.8-μm rule)
Standby current (per cell)	10^{-15} A	10^{-12} A	10^{-13} A

Use high Vt

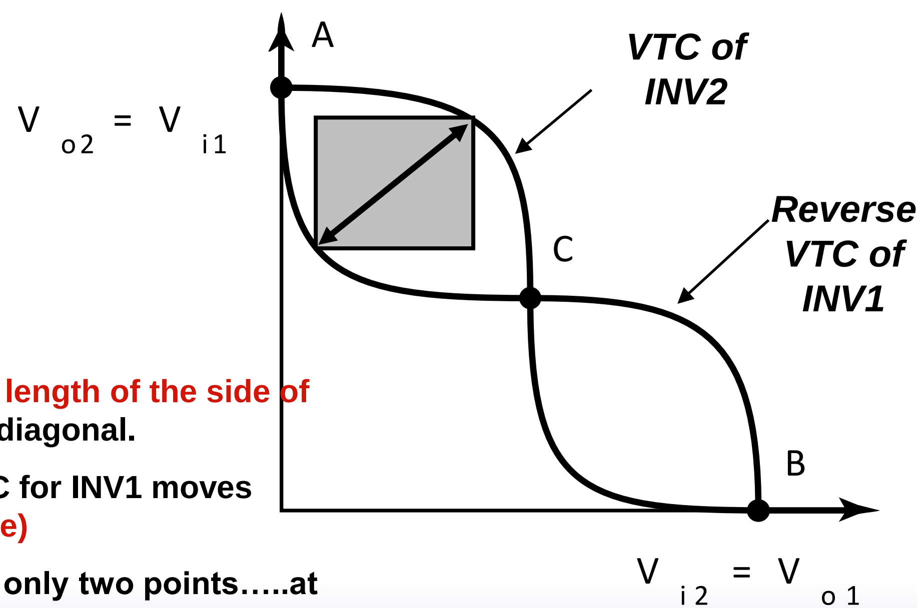
However, embedded SRAM cells---used in microprocessor caches, employ 6T cells.

6-T CMOS SRAM Cell: Static Noise Margin





Butterfly Curve



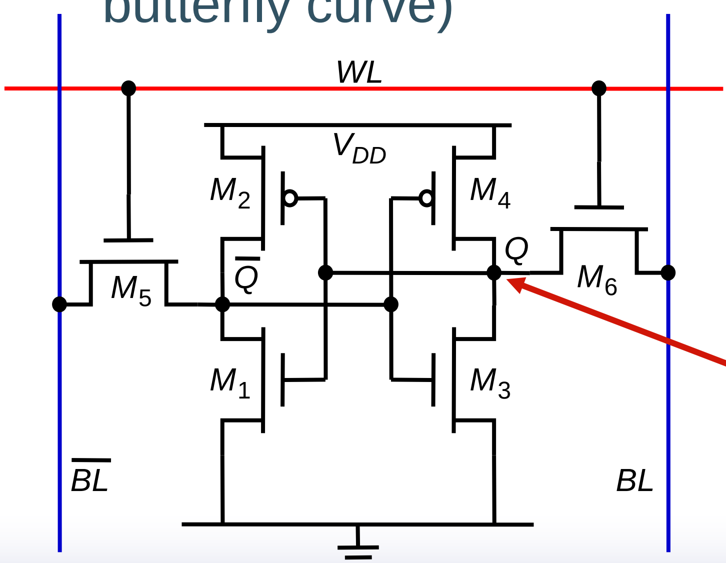
The SNM (hold margin) can be estimated graphically by the length of the side of the square fitted between the VTCs and having the longest diagonal.

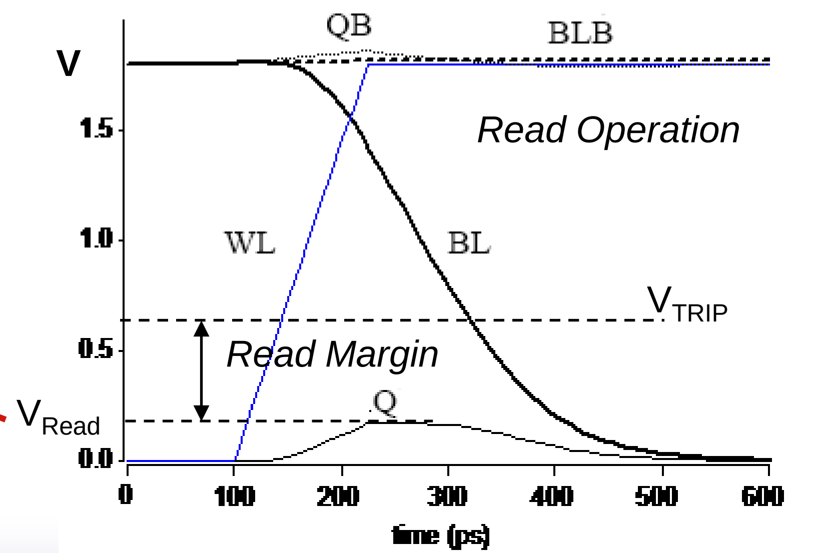
As noise increases at the two nodes above, the reverse VTC for INV1 moves upward, while the VTC for INV2 moves to the left (worst case)

Once they both move by the SNM value, the curves meet at only two points…..at A' and B'…… and any further noise flips the data.

Static Noise Margin (SNM)

- **Hold Margin:** How strongly the node storing ‘1’ and the node storing ‘0’ are coupled to V_{DD} and V_{SS} respectively.
- **Read Margin:** The difference between V_{TRIP} and V_{READ} (max. voltage at Q)
- **Write Margin**: The maximum voltage on a bit-line that allows writing to the cell, while the other bit-line is at V_{DD}. (not determined by the butterfly curve)

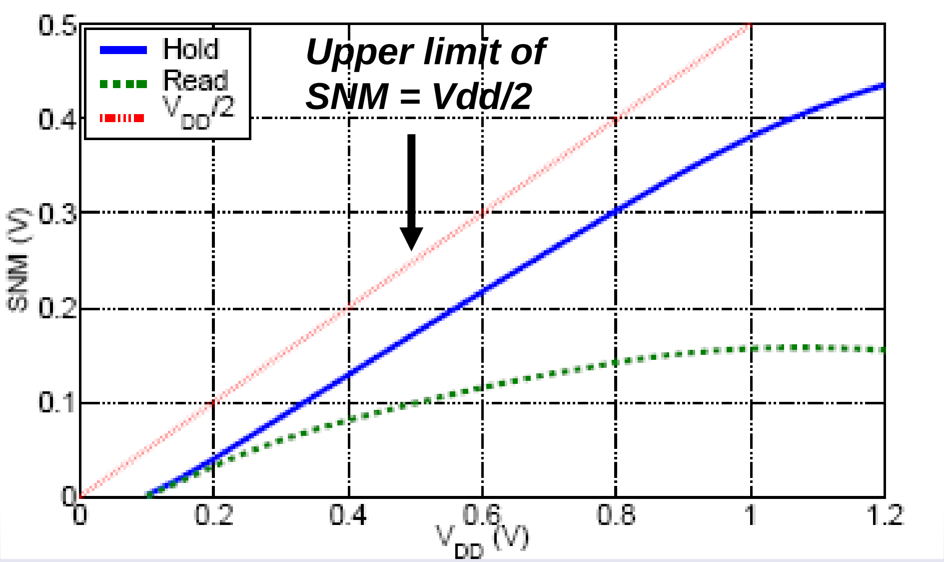




SNM Dependencies

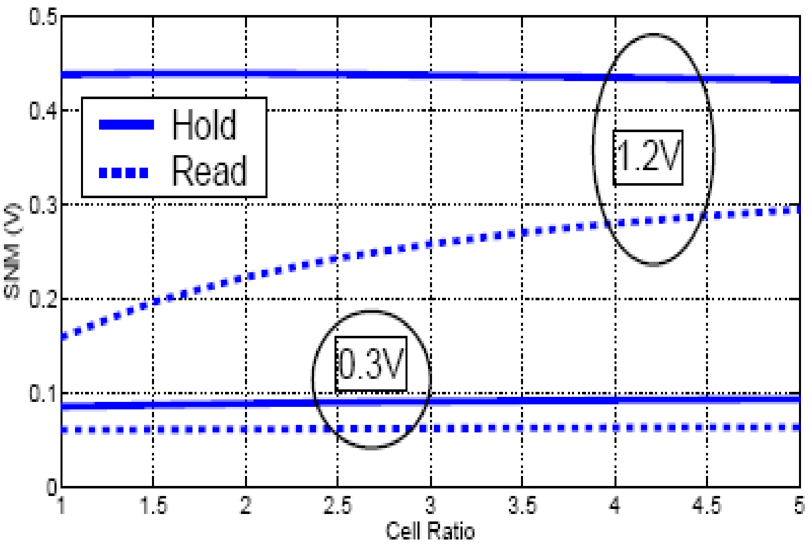
- Dependence on V_{dd} : SNM for a bitcell with ideal VTCs is still limited to Vdd/2. Any noise > Vdd/2 will flip the inverters.

Read margin increases with Vdd since Vtrip (=Vdd/2) increases…



- Dependence on sizing

Here, Cell ratio = size of PD device over size of access device



Read-SNM increases with cell ratio (increasing Pull-down device) since bigger PD device reduces the V_Q

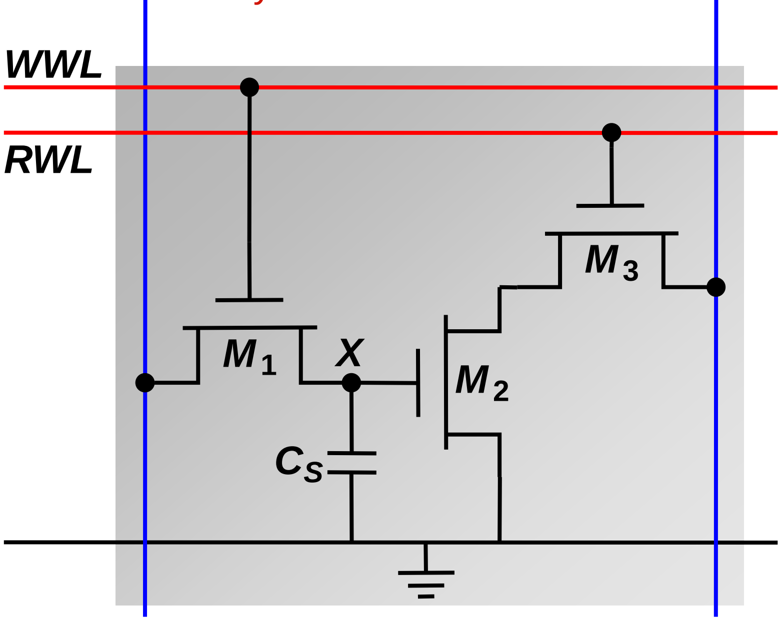
3-Transistor DRAM Cell (Early Days)

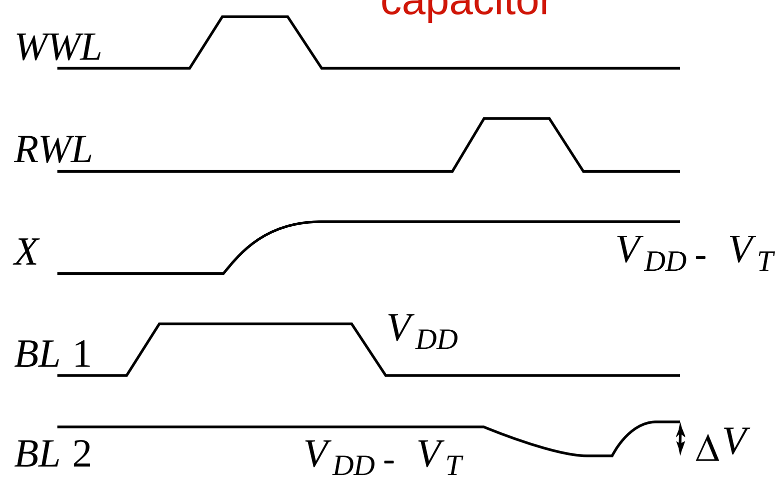
1 Kbit memory: Intel

Still used in some ASICs

Periodic refresh operation consists of **read** followed by **write**

Dynamic: since it involves charge storage on a capacitor





Cell is written by placing value on BL1 and asserting Write Word Line (WWL=1)

Data retained as charge stored on Cs once WWL=0

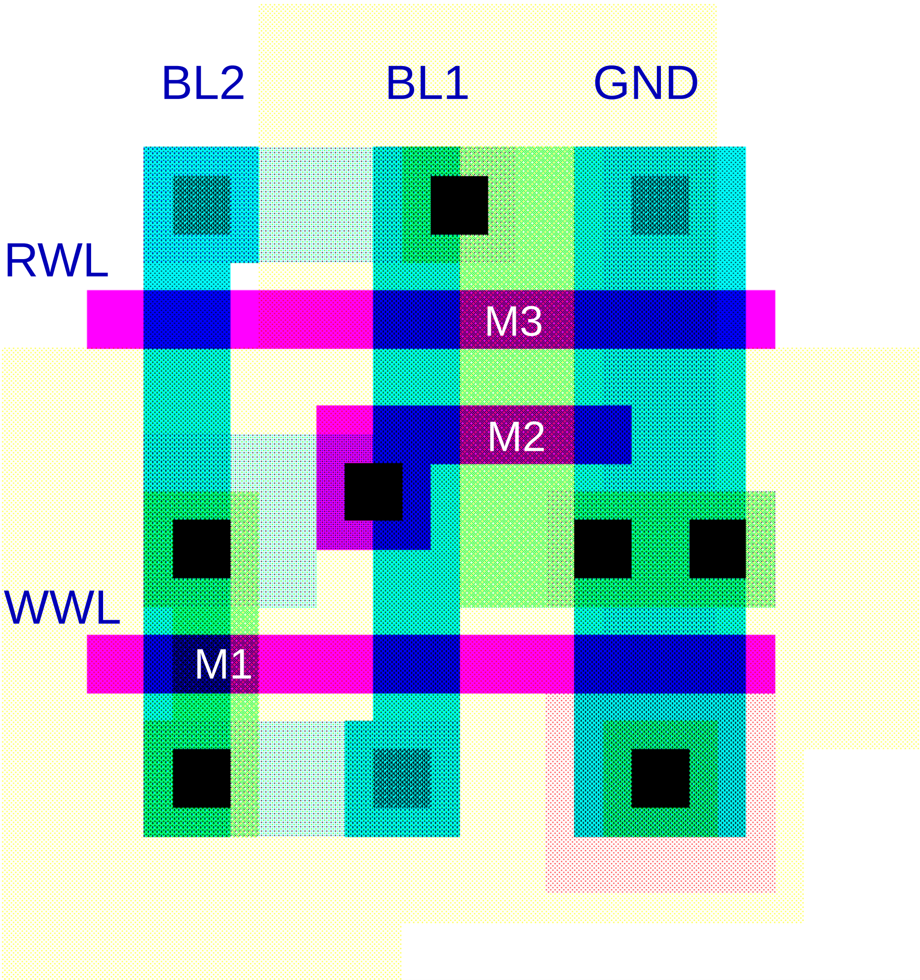
For reading the cell, RWL=1

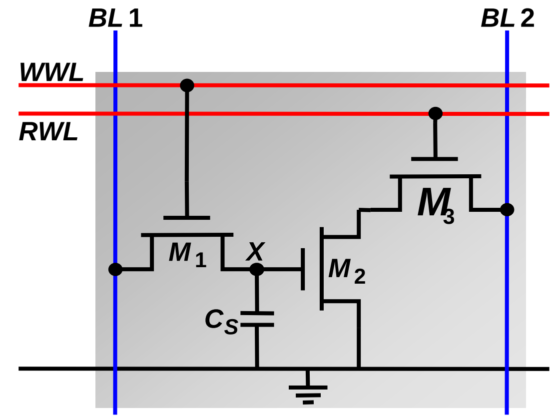
M2 can be on or off depending on stored value

BL2 is either clamped to Vdd or is precharged to either Vdd or Vdd-Vt

M2-M3 pulls BL2 low when X=1, otherwise BL2 remains high (cell is inverting: senses the inverse value of the stored signal)

3T-DRAM — Layout





Unlike SRAM, no constraint on device sizes

Read operation is non-destructive

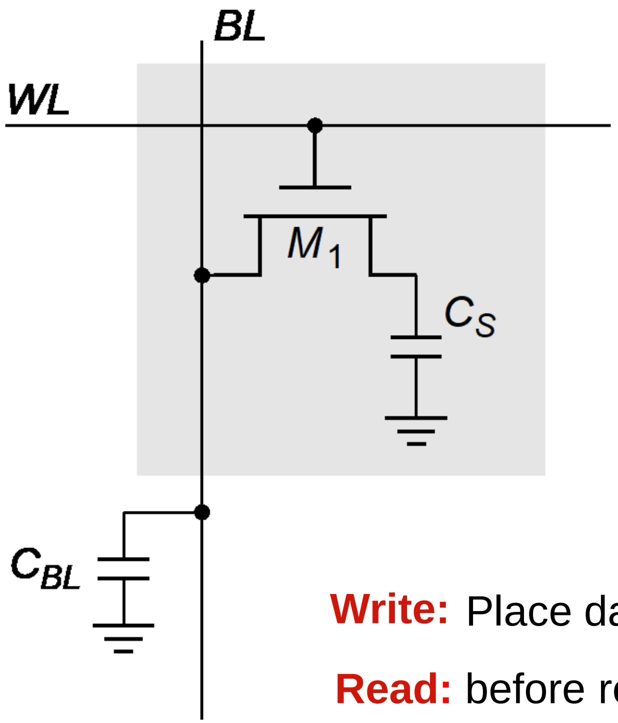
No special process steps needed

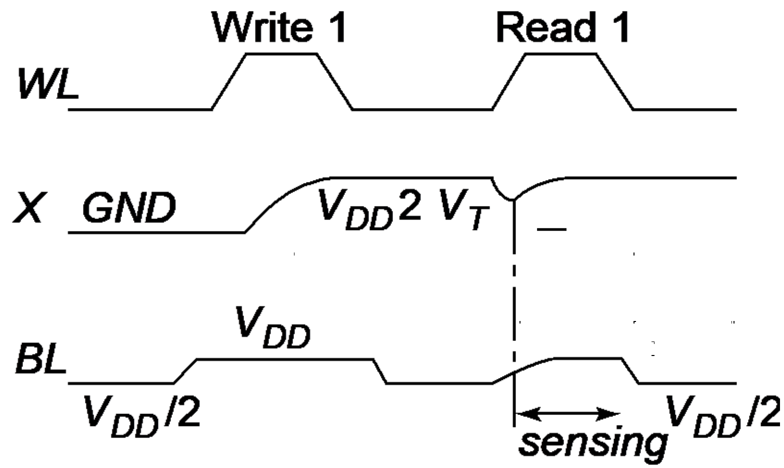
Value at node X = V_{WWL} - V_{tn}

This reduces the current through M2 during read operation and increases read access time: can use a higher value of V_{WWL} to avoid this

1-Transistor DRAM Cell

Most pervasive in commercial memory design





Write: Place data on BL and assert WL, depending on data value, Cs is 1 or 0

Read: before read, precharge BL to V_{PRE}

After WL=1, charge redistribution takes places between bit line and storage capacitance resulting in a voltage change on BL

$$\Delta V = V_{BL} - V_{PRE} = (V_{BIT} - V_{PRE}) \frac{C_S}{C_S + C_{BL}}$$

← Charge transfer ratio (1-10%)

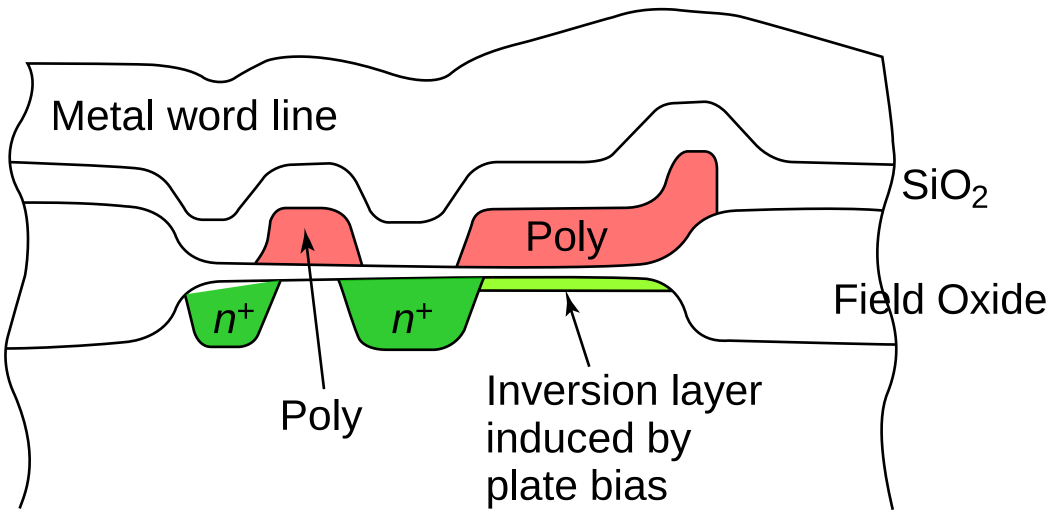
V_{BIT} is initial voltage on C_s. V_{BL} is final voltage on BL after charge redistribution. Voltage swing is small since $C_s \ll C_{BL}$; typically around 250 mV.

Note: *From charge conservation,* $C_S V_{BIT} + C_{BL} V_{PRE} = (C_S + C_{BL}) V_{final}$, *and* V_{final} (= $\mathbf{V_{BL}}$)

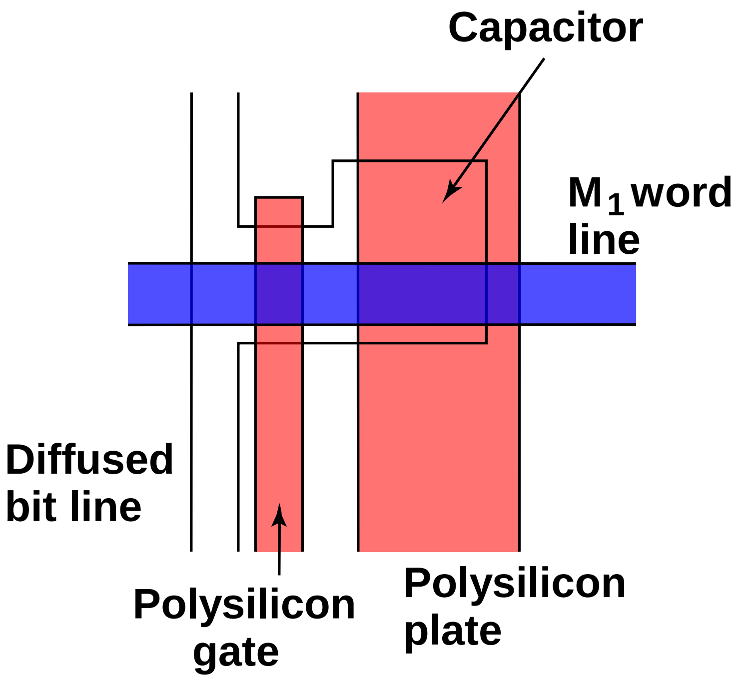
DRAM Cell Observations

- 1T DRAM requires a sense amplifier for each bit line, due to charge redistribution read-out.
- DRAM memory cells are single ended in contrast to SRAM cells.
- The read-out of the 1T DRAM cell is destructive; read and refresh operations are necessary for correct operation.
- Unlike 3T cell, 1T cell requires presence of an extra capacitance that must be explicitly included in the design.
- When writing a "1" into a DRAM cell, a threshold voltage is lost. This charge loss can be circumvented by bootstrapping the word lines to a higher value than V_{DD}

1-T DRAM Cell



Cross-section

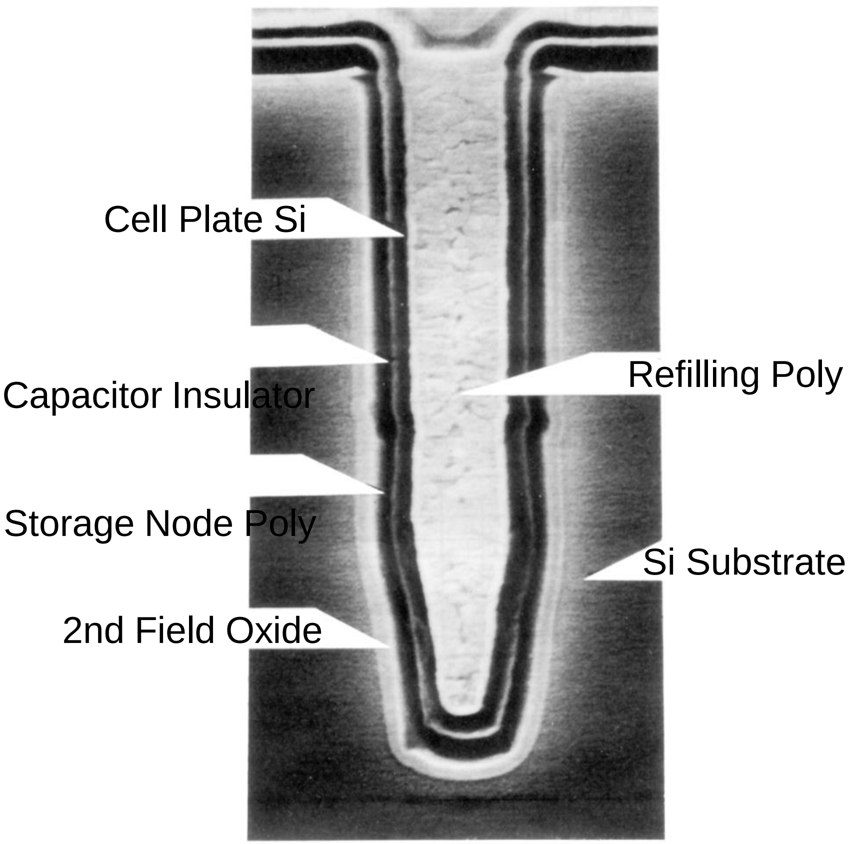


Layout

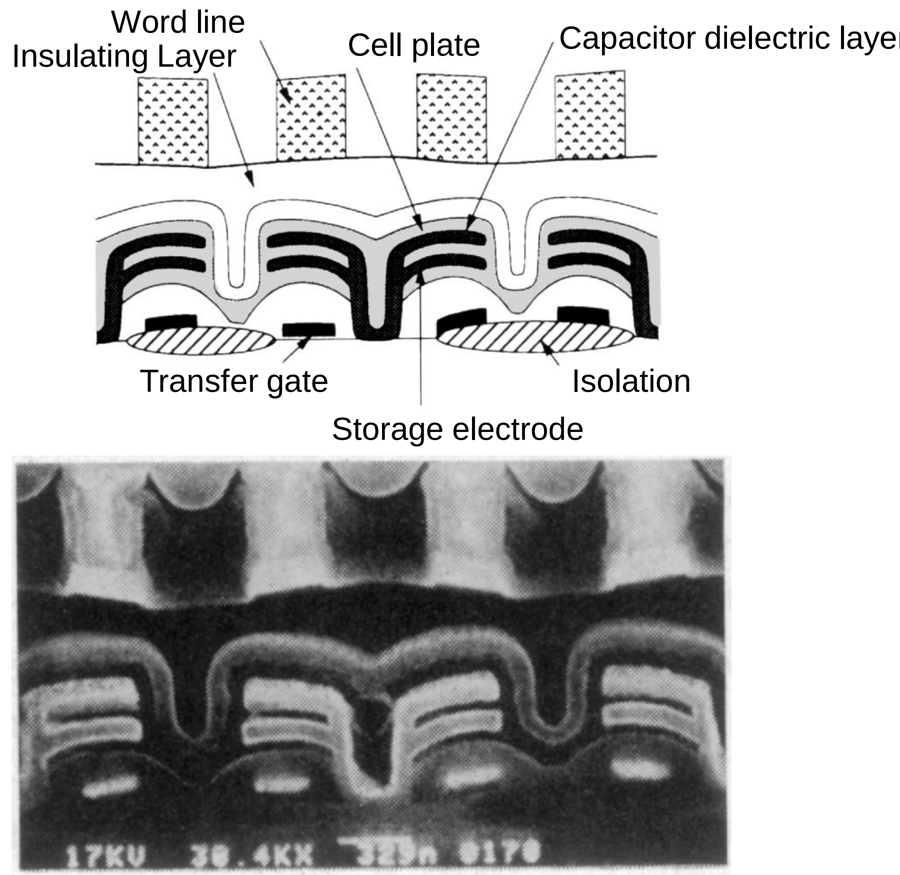
Uses Polysilicon-Diffusion Capacitance

Expensive in Area

Advanced 1T DRAM Cells



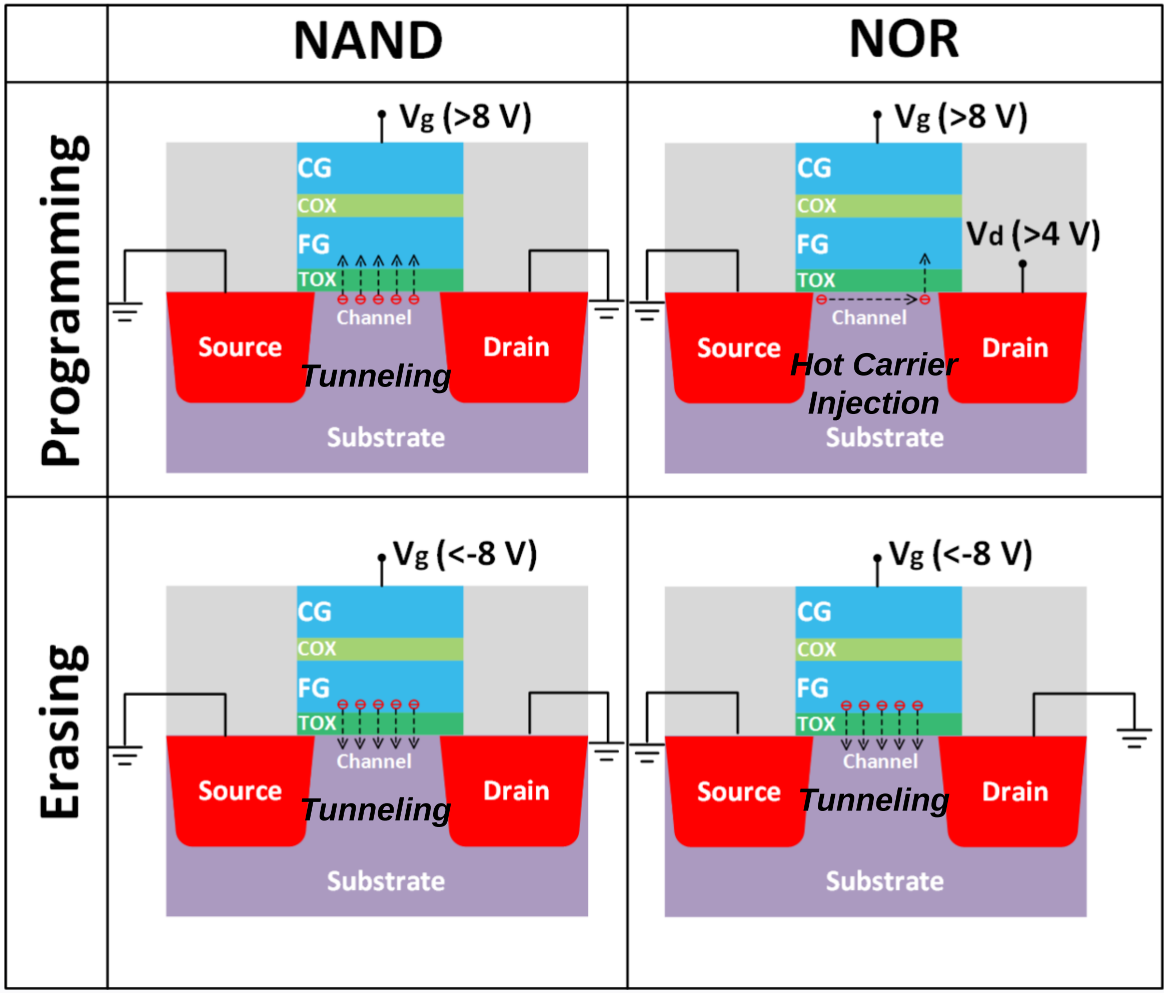
Trench Cell



Stacked-capacitor Cell

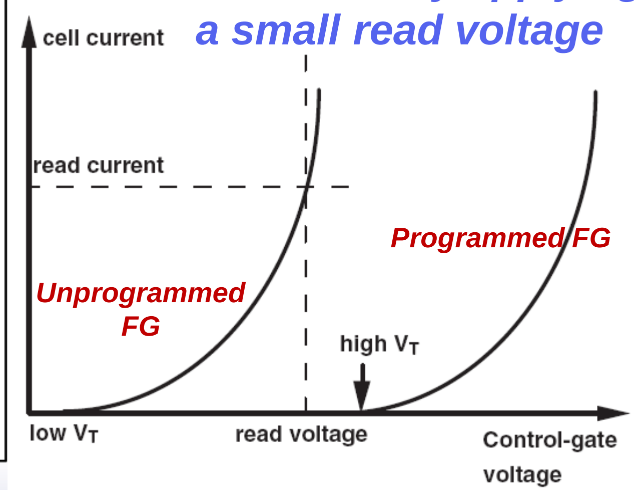
Non-Volatile Memory

Flash Memory *(with Floating Gate (FG) Transistor)*



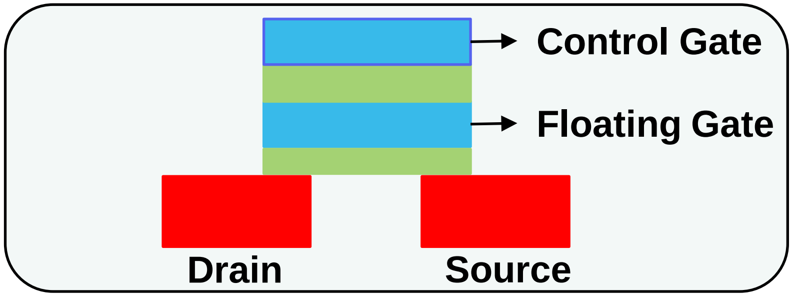
N-type device
CG: control gate
COX: control oxide
FG: floating gate
TOX: tunnel oxide

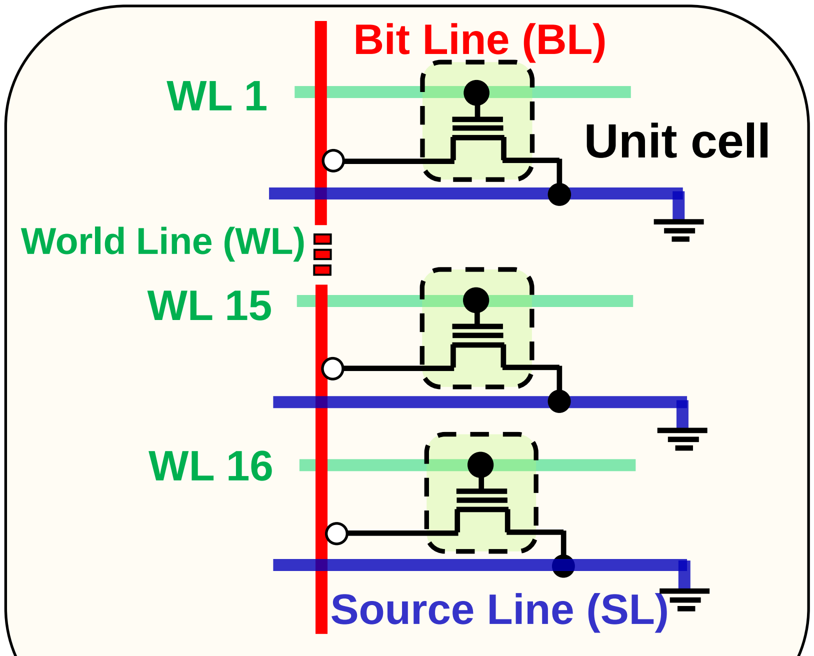
Read-out: by applying a small read voltage



NAND vs. NOR circuit

NOR-EEPROM



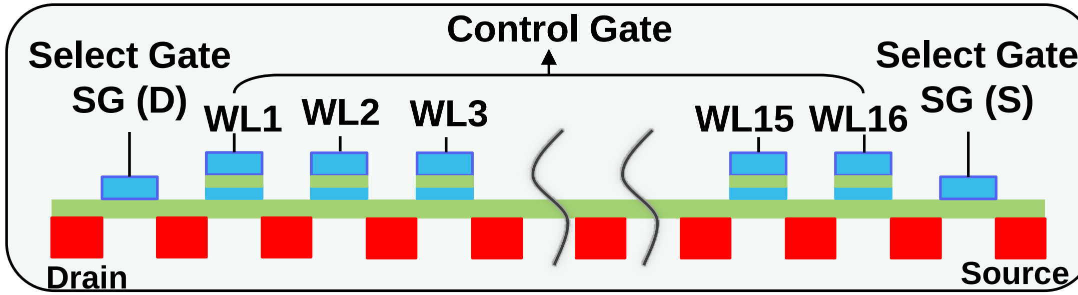


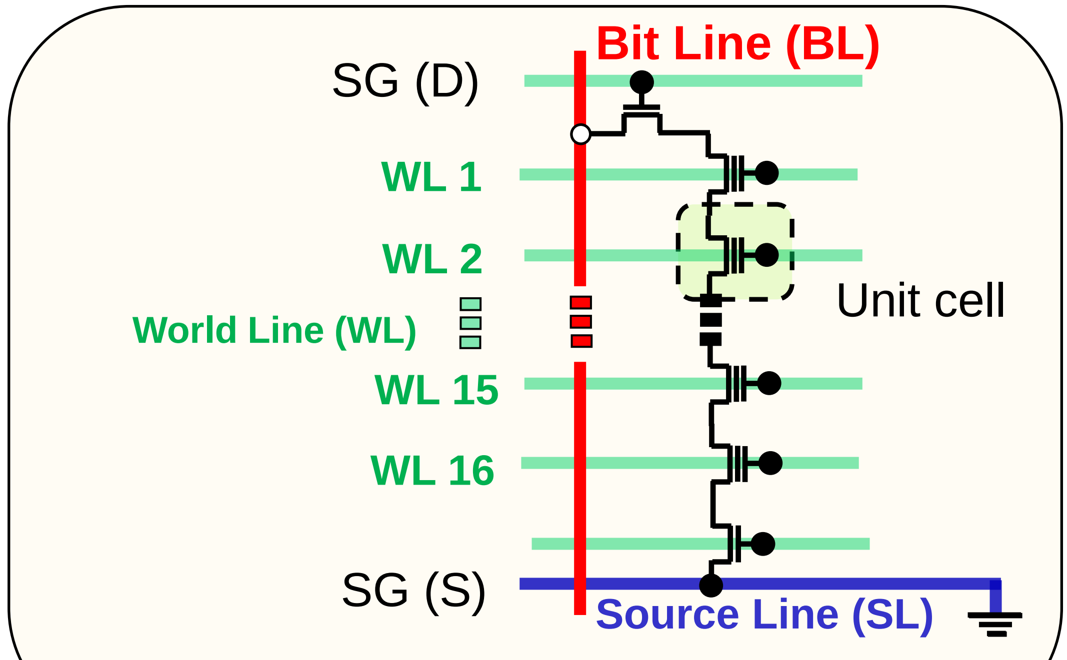
1 Transistor/ 1 Bit

Devices can be Randomly accessed

NOR: It's available for random access

NAND-EEPROM





18 Transistor/ 16 Bit

Both SG devices needed for read out

NAND: It's allowed to access one bit only per readout operation

NAND vs. NOR

Merits of NAND

★ *Multiple cells at once*

① **High speed programming** (★)
② **High speed erasing**
③ **High capacity**
④ **Low cost per bit**

Merits of NOR

① **High speed random access**
② **Bit programming**

(Individual bit cell for programming/erasing process)

Demerits of NAND

① **Slow random access**
② **Bit programming cannot be performed**
③ **Slow read operation**

(Serial access => sequential data readout)

Demerits of NOR

① **Slow programming**
② **Slow speed erasing**
③ **Low capacity**
④ **High cost per bit**

(NOR must be erased in large "chunks". Those chunks can often be subdivided and erased in smaller subunits resulting in a performance penalty)

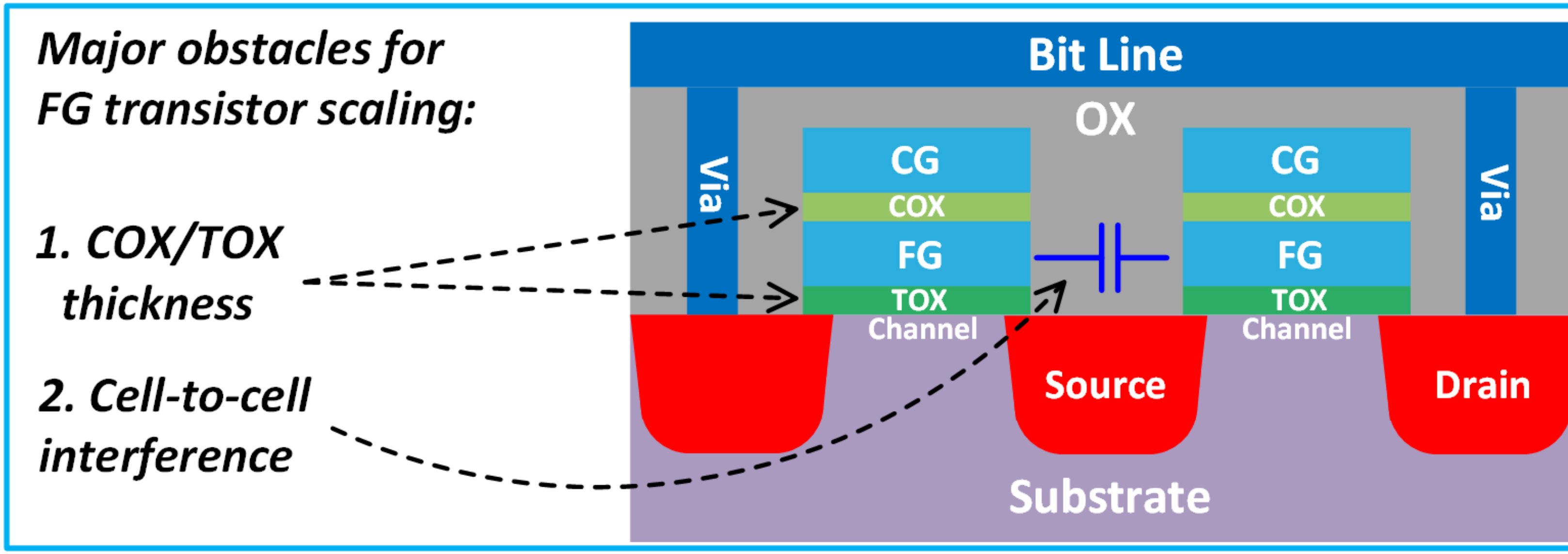
- Applications -

- **Suitable for Data Memory (Handy terminal, Voice recorder, DSC, Fax modem, etc)**

- Applications -

- **Suitable for replacement of EPROM**
- **Suitable for control memory (BIOS, Cellular, HDD, etc)**

Scaling issues

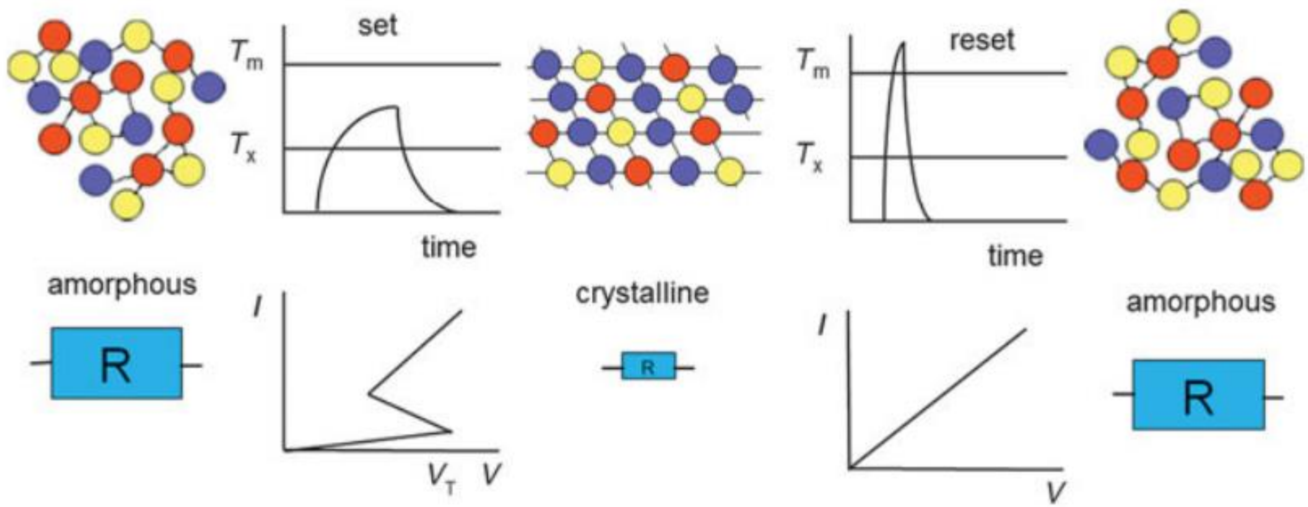


- thin COX/TOX -> leakage current -> short retention time
- small cell-to-cell distance -> Vth perturbation by adjacent cells

Promising solution: 2D materials….

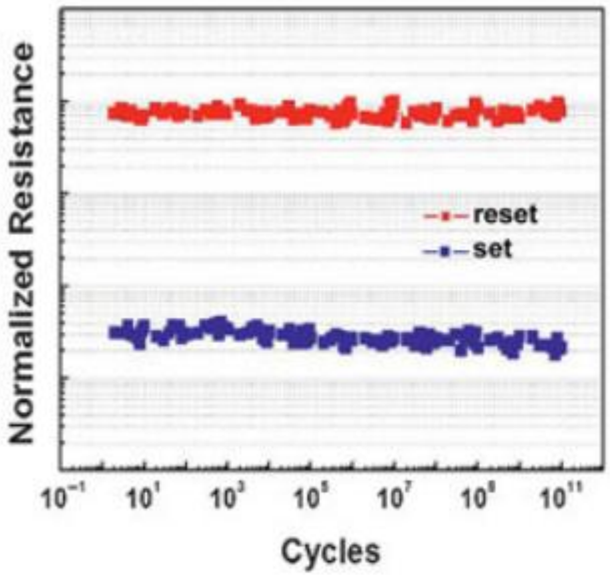
Can 2D-Nanocrystals Extend the Lifetime of Floating-Gate Transistor Based Nonvolatile Memory?
Wei Cao, Jiahao Kang, Simone Bertolazzi, Andras Kis and Kaustav Banerjee
IEEE Transactions on Electron Devices, vol. 61, No. 10, pp.3456-3464, 2014.

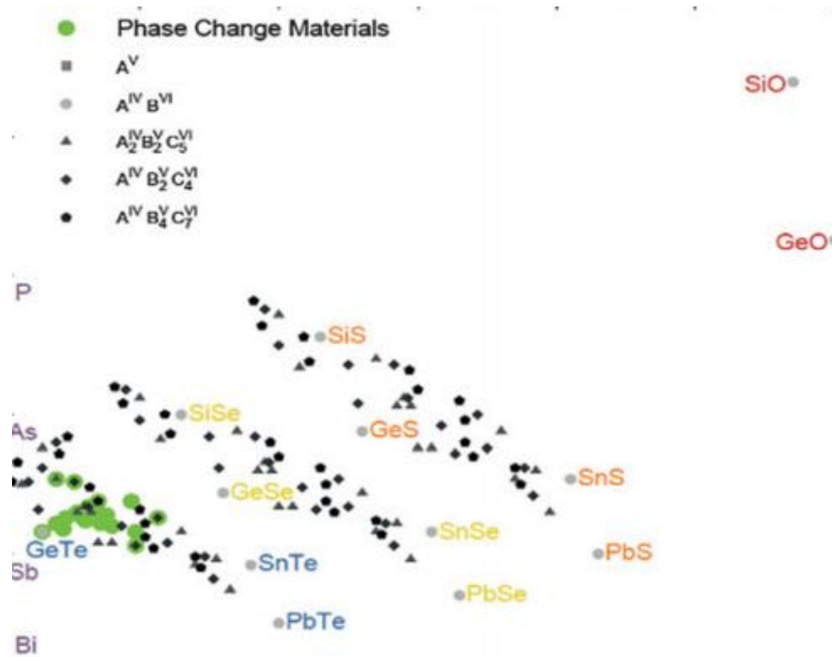
Phase Change RAM



- Works on repeated switching of phase change material between the amorphous (high-resistance) and crystalline (low-resistance) states by application of a suitable electrical current.
- A large current pulse is applied to an amorphous material which heats it up, leading to a threshold voltage shift to a lower value, causing a sudden increase in current. Joule heating from this heats up the material beyond crystallization temperature (T_X) and the material changes to a crystalline state.
- Under application of an even larger sharp current pulse, the crystalline material melts (melting temperature T_M) and then solidifies to an amorphous state.

Phase Change RAM



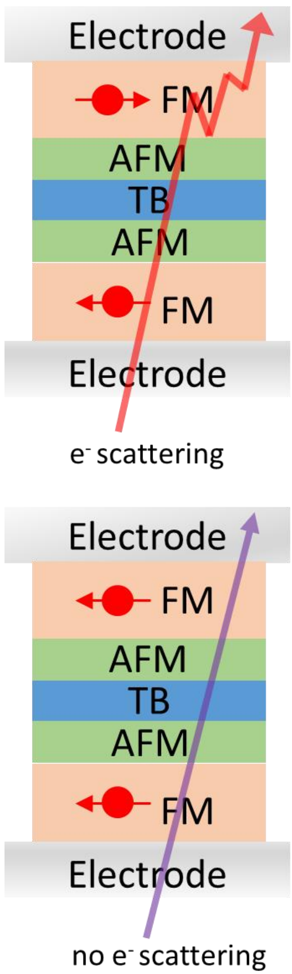


- Switching from an amorphous to a crystalline state and vice-versa happens in nanoseconds, much faster than a flash memory, and is comparable to SRAMs

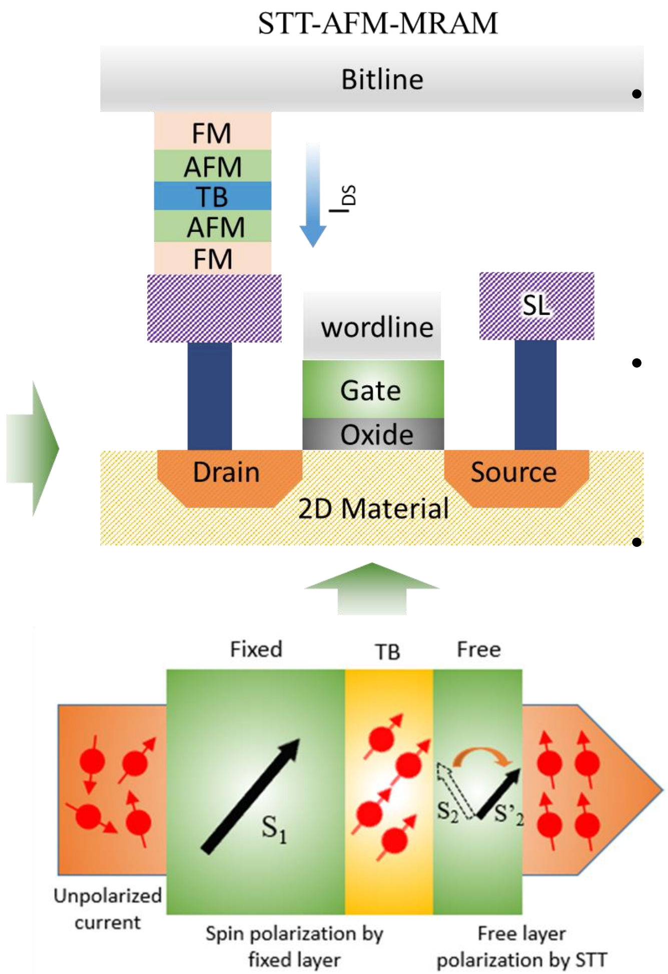
- PCRAMs can endure a read/write cycle of up to 100 million times while a set/reset resistance ratio of 3 orders ensures robust noise margin

- Main challenges to implementation are the requirement of a large cell size (small cell size can cause appreciable heating during a read operation), electromigration due to increased heating, and CMOS compatible crystallization and melting temperatures.

Spin Torque Transfer RAM



Read Operation



Write Operation

- STTMRAM is a building component of a MRAM. Polarization of one fixed layer of Ferro-Magnet (FM) and one free FM are tuned to change from a low-resistance to a high resistance state
- Spin polarized electric current can tune the polarization of the free layer of FM by exerting Spin Transfer Torque (STT)
- During a read operation a small current is pulsed from the bottom to the top electrode. Electrons passing through the bottom layer of spin polarized FM are spin polarized and scatter off from the top layer of FM if it has an opposite spin polarization leading to a high resistance. Same spin electrons suffer no scattering and register a low resistance.

Spin Torque Transfer RAM

- Figure of merit of STT-MRAM is defined by a Giant Magnetoresistance (GM) ratio given by

$$GM = \frac{R_{AP} - R_P}{R_P}$$

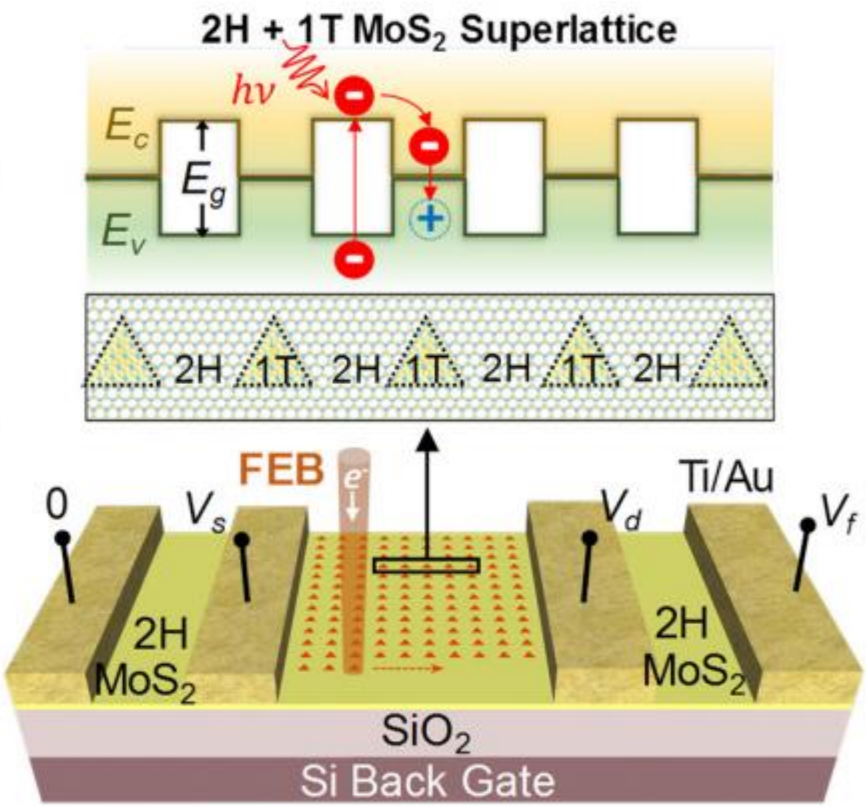
where, R_P = resistance when the FM layers have parallel polarization
R_{AP} = resistance when FM layers have anti-parallel polarization

- Has the potential to be scaled down to sub-10 nm regimes without sacrificing performance as the relatively huge GM of STT-MRAMs guarantees adequate performance

- Switching speeds can be as low as few tens of nano-seconds at only 7.5 microamps of current.

- Relatively large cost of implementation is the bottleneck right now for their implementation

Memristor



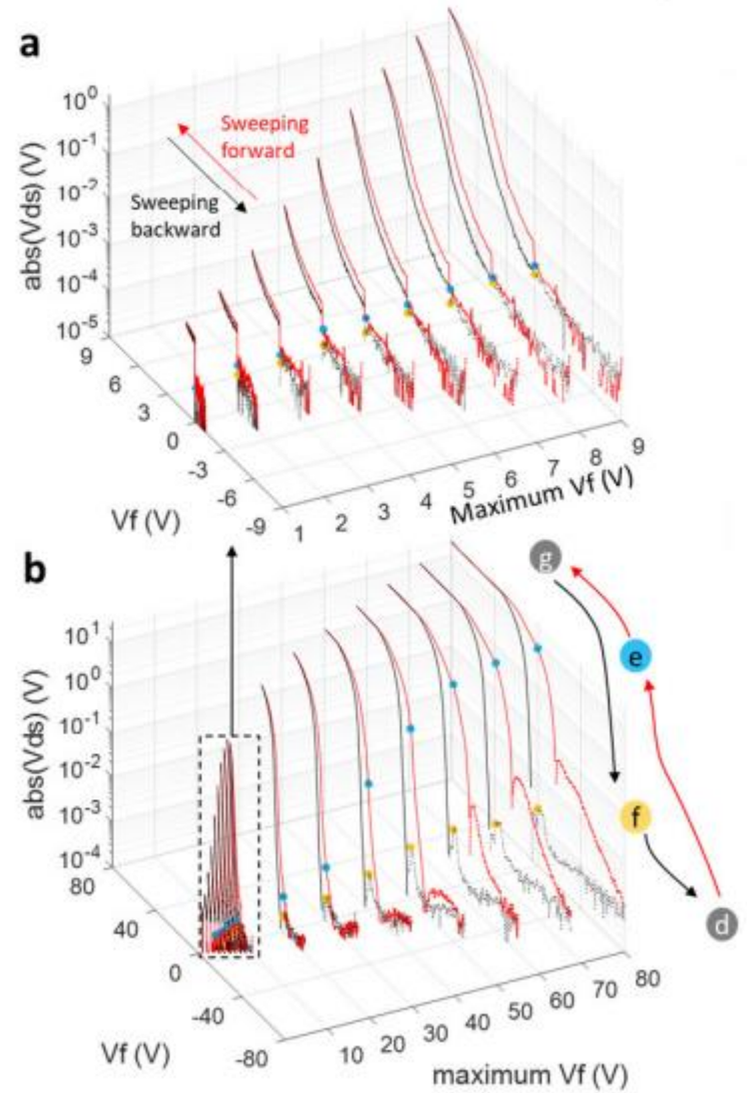
- A memristor is an electrical device whose electrical resistance is not constant, but instead, is dependent on the history of electrical current flown through it.
- Various classes of memristor proposed – titanium dioxide, polymeric, layered, ferroelectric and so on..
- A memristor can retain most of its memory of resistance even when power is switched off – non volatile memory
- A memristive transistor (shown of the figure) was shown by selectively irradiating specific spots on a MoS_2 crystal with e-beam to induce a phase transformation of a metallic 1T- phase from semiconducting 2H-phase
- Quantum dots thus produced can store charge when current is pumped through, thereby altering the resistance state

Memristor

- As seen from the voltage sweeps on the right, the resistance of the memristor is dependent on the direction of the sweep. This hysteresis behavior also changes the resistance of the transistor during both forward and reverse sweeps.

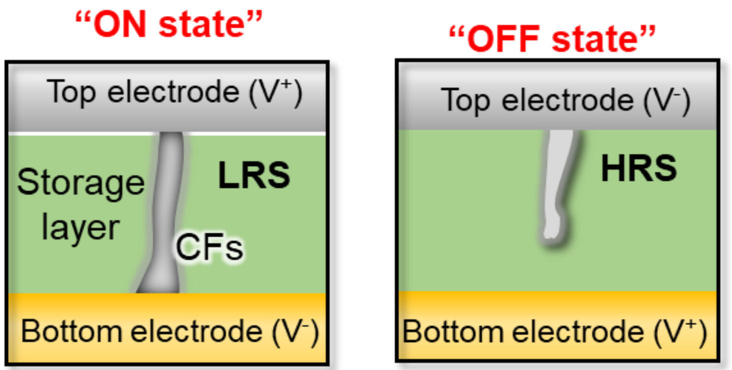
- Light excitation can also pump charge into the system thereby modulating the electrical resistance.

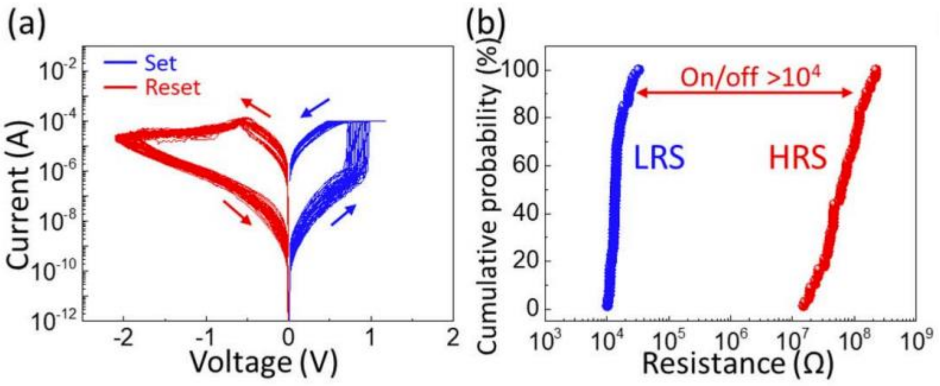
- Can offer very low latency times for read/write (in order of few ns) with potential for ultimate scalability in the order of sub-10 nm



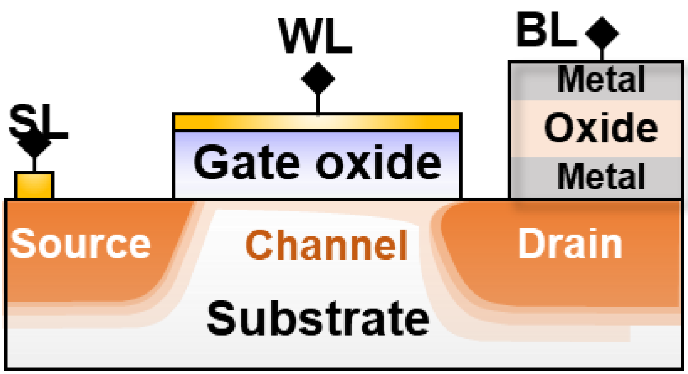
Resistive RAM (RRAM):

- Non-volatile memory element whose resistance states are dependent on past programming.
- Works on the principle of creation and rupture of conducting filament.
- Generally, a transistor connected in series is used to source the programming current.





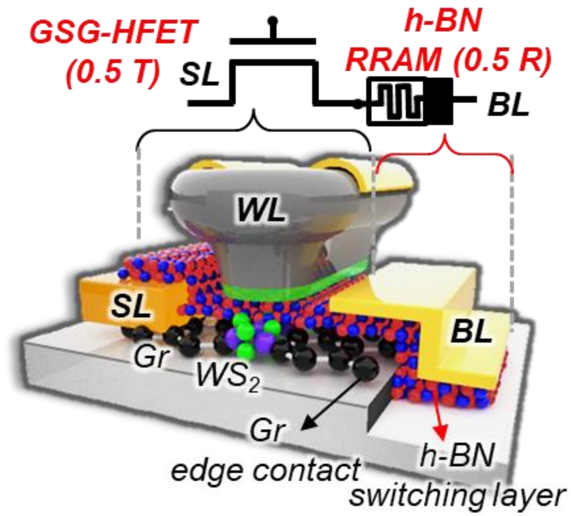
RRAM switching characteristics



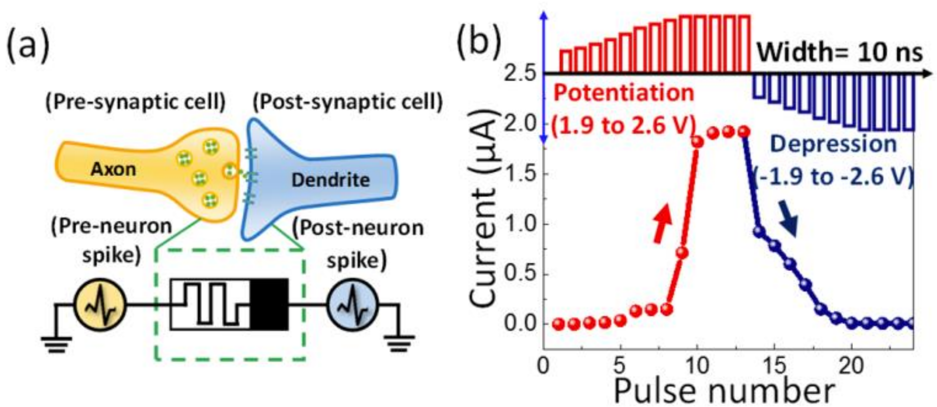
Traditional RRAM

Resistive RAM (RRAM):

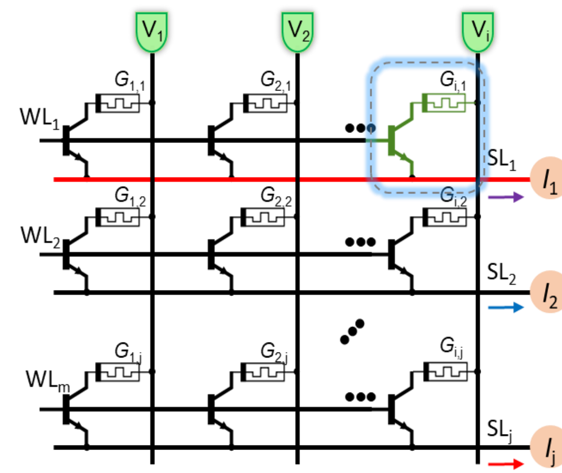
- The transistor and memory units were uniquely coupled in the 0.5T0.5R-RRAM device, demonstrating enhanced scalability, lower energy and record performance
- Can further be used for demonstrating synaptic behavior in neuromorphic (NM) circuits and multiply-accumulate operation in in-memory computing.



0.5T0.5R-RRAM

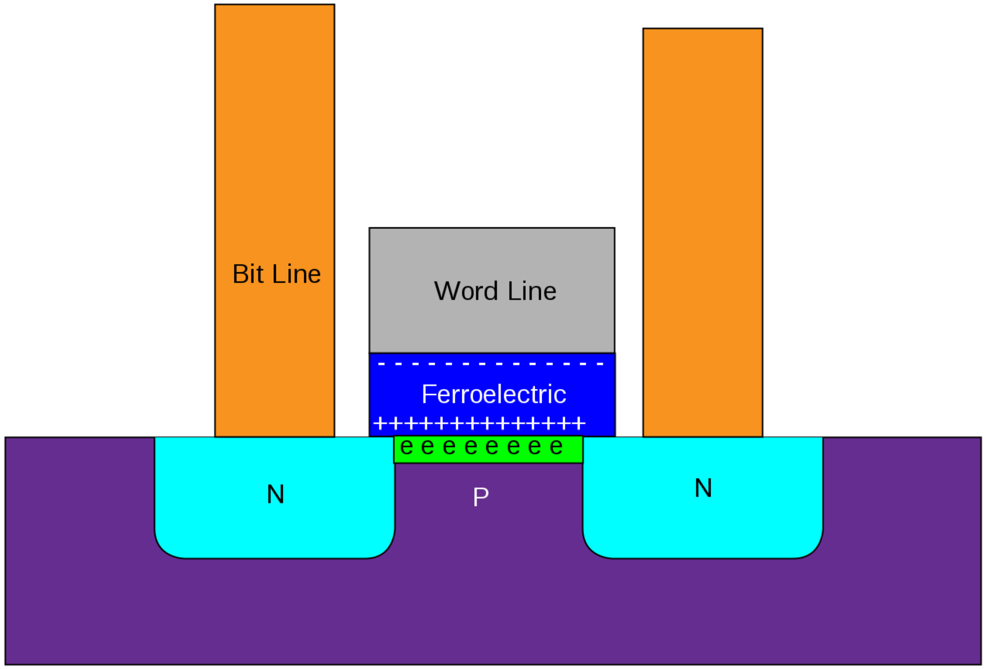


Application in NM computing



MAC operation in in-memory computing

Ferroelectric RAM



Once a particular state is written, the polarization charges are held across the Ferroelectric.

Because of the absence of periodic refresh as in DRAM cells, the power consumption is substantially smaller. Main drawback is the robustness, with extensive cycling leading to a loss of polarization

- Utilizies a ferro-electric layer with free polarization charges to induce carrier formation in the access transistor channel. This modulates the electrical resistance of the transistor, thereby acting as a memory element.
- Used ferroelectric material is generally lead zirconate titanate (PZT)
- Switching speed of FeRAM depends on the speed of the physical movement of polarization charge which can be as small as few nanoseconds.