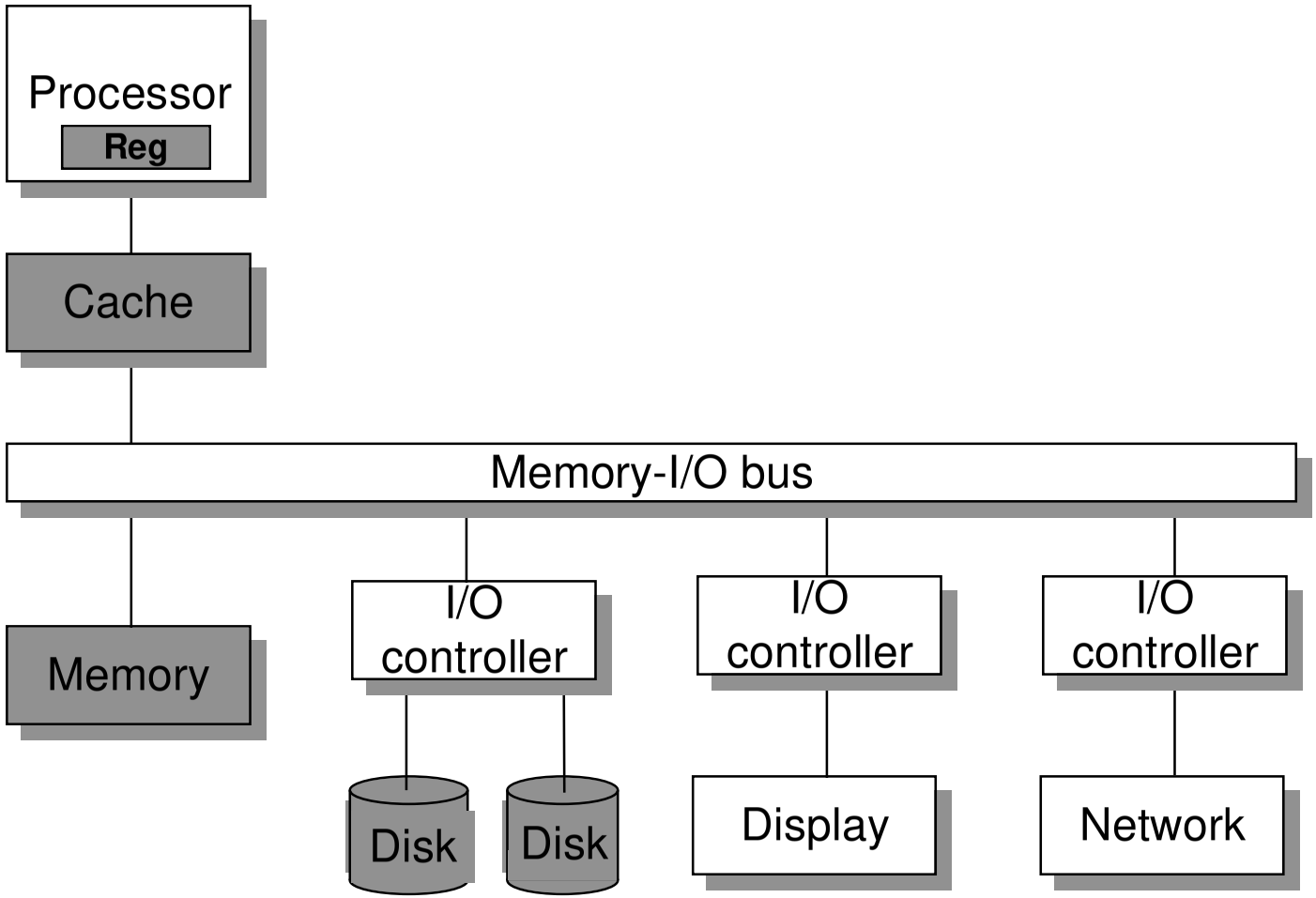
Memory Technology
15-213

Oct. 20, 1998

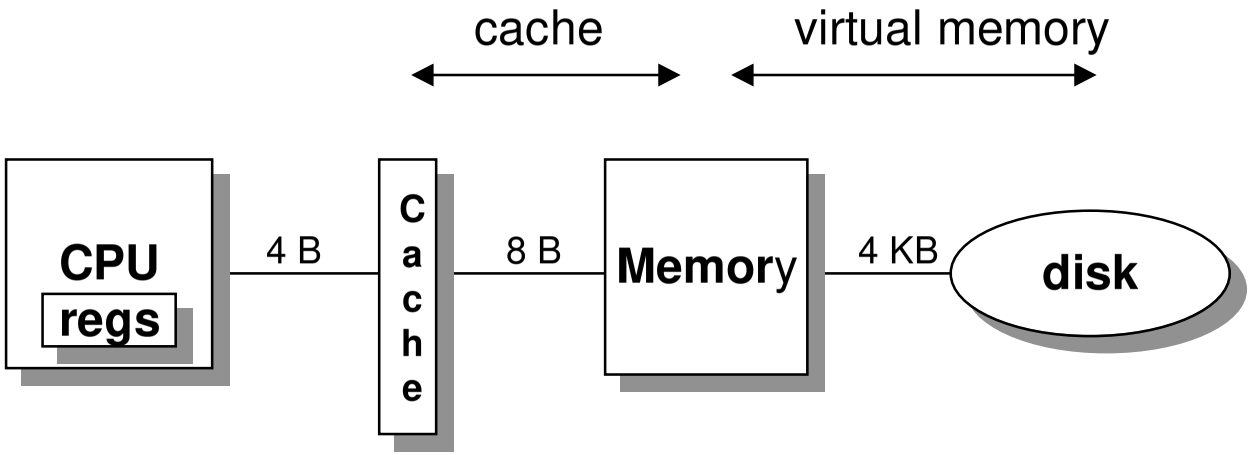
Topics

- Memory Hierarchy Basics
- Static RAM
- Dynamic RAM
- Magnetic Disks
- Access Time Gap

Computer System



Levels in Memory Hierarchy



	Register	Cache	Memory	Disk Memory
size:	200 B	32 KB / 4MB	128 MB	20 GB
speed:	3 ns	6 ns	100 ns	10 ms
$/Mbyte:		$100/MB	$1.50/MB	$0.06/MB
block size:	4 B	8 B	4 KB	

larger, slower, cheaper

Scaling to 0.1μm

- **Semiconductor Industry Association, 1992 Technology Workshop**
  - Projected future technology based on past trends

Year	1992	1995	1998	2001	2004	2007
Feature size	0.5	0.35	0.25	0.18	0.12	0.10

  - Industry is slightly ahead of projection

DRAM cap	16M	64M	256M	1G	4G	16G

  - Doubles every 1.5 years
  - Prediction on track

Chip cm^2	2.5	4.0	6.0	8.0	10.0	12.5

  - Way off! Chips staying small

Static RAM (SRAM)

Fast

- ~6 ns [1998]

Persistent

- as long as power is supplied
- no refresh required

Expensive

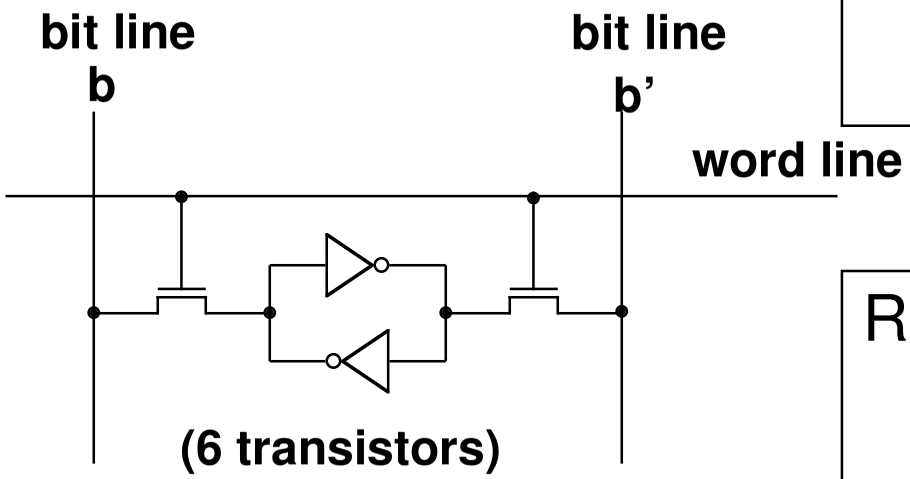
- ~$100/MByte [1995]
- 6 transistors/bit

Stable

- High immunity to noise and environmental disturbances

Technology for caches

Anatomy of an SRAM Cell



Write:
- set bit lines to opposite values
- set word line
- Flip cell to new state

Read:
- set bit lines high
- set word line high
- see which bit line goes low

Stable Configurations

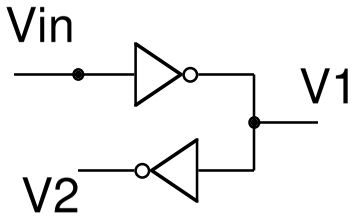
SRAM Cell Principle

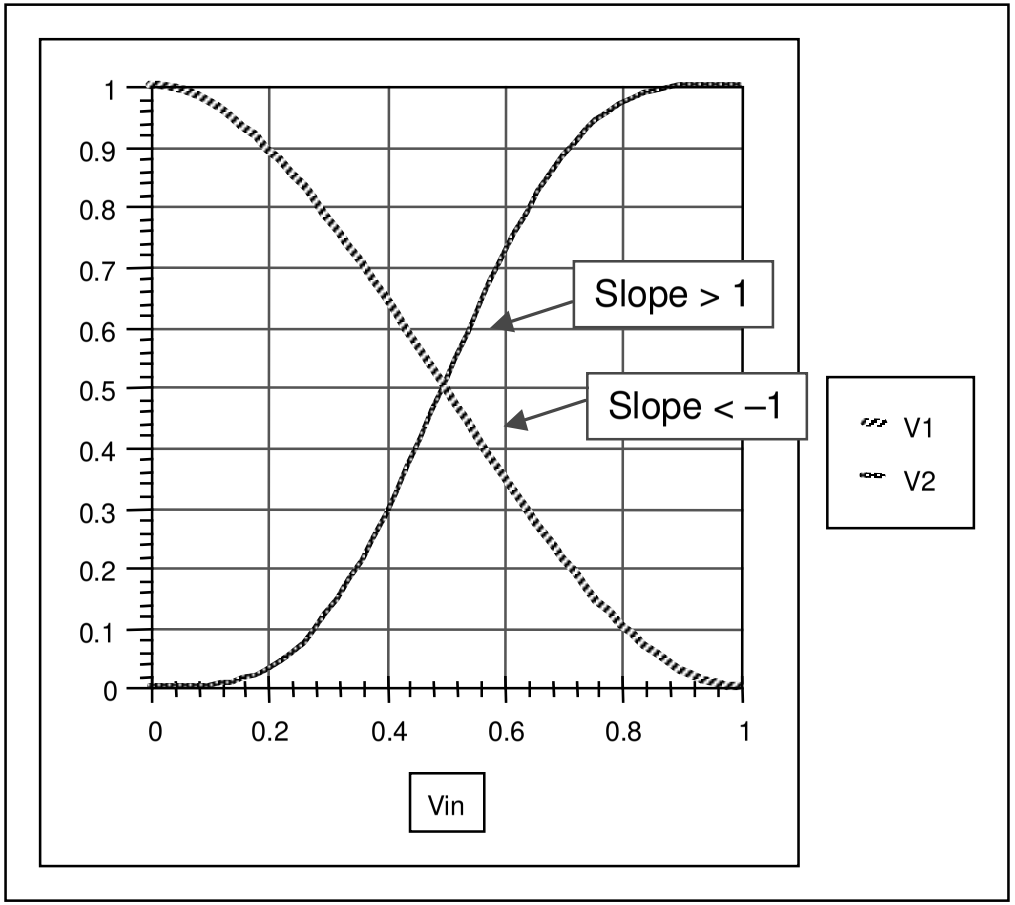
Inverter Amplifies

- Negative gain
- Slope < –1 in middle
- Saturates at ends

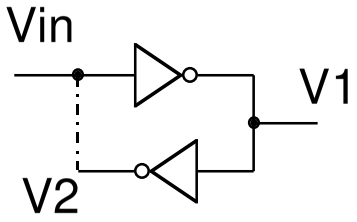
Inverter Pair Amplifies

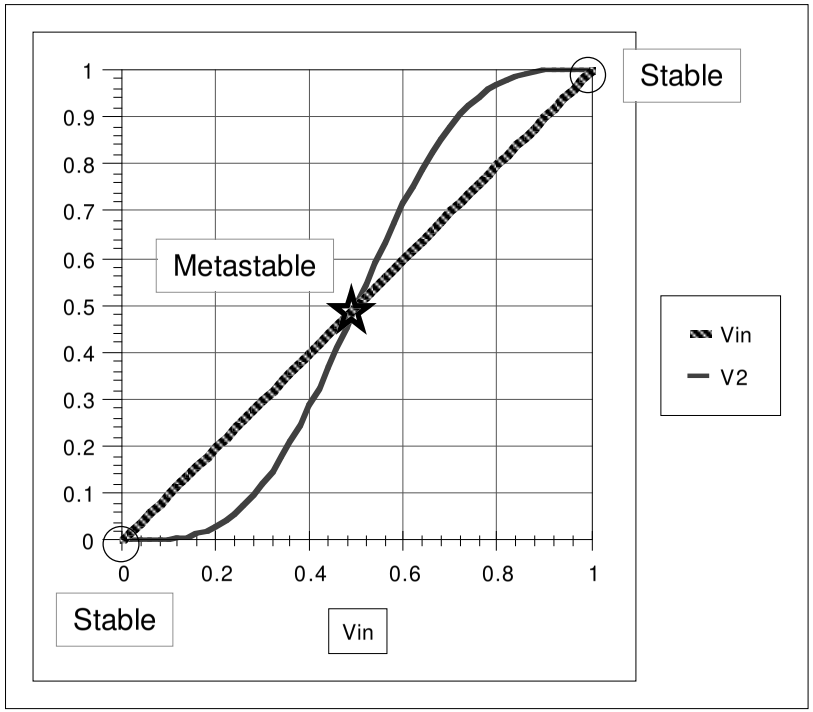
- Positive gain
- Slope > 1 in middle
- Saturates at ends





Bistable Element

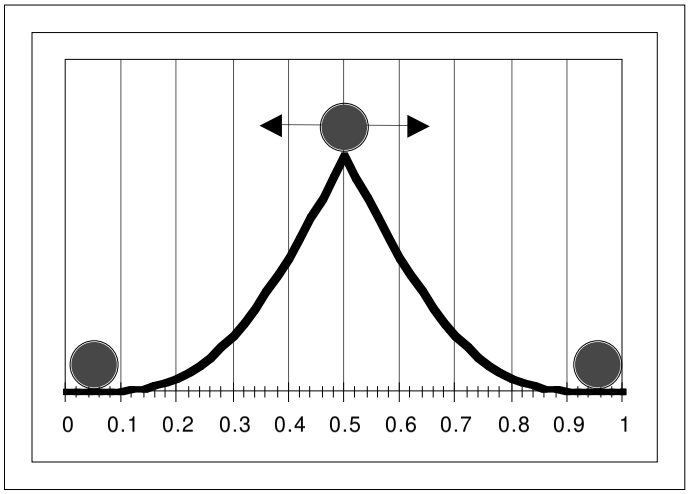




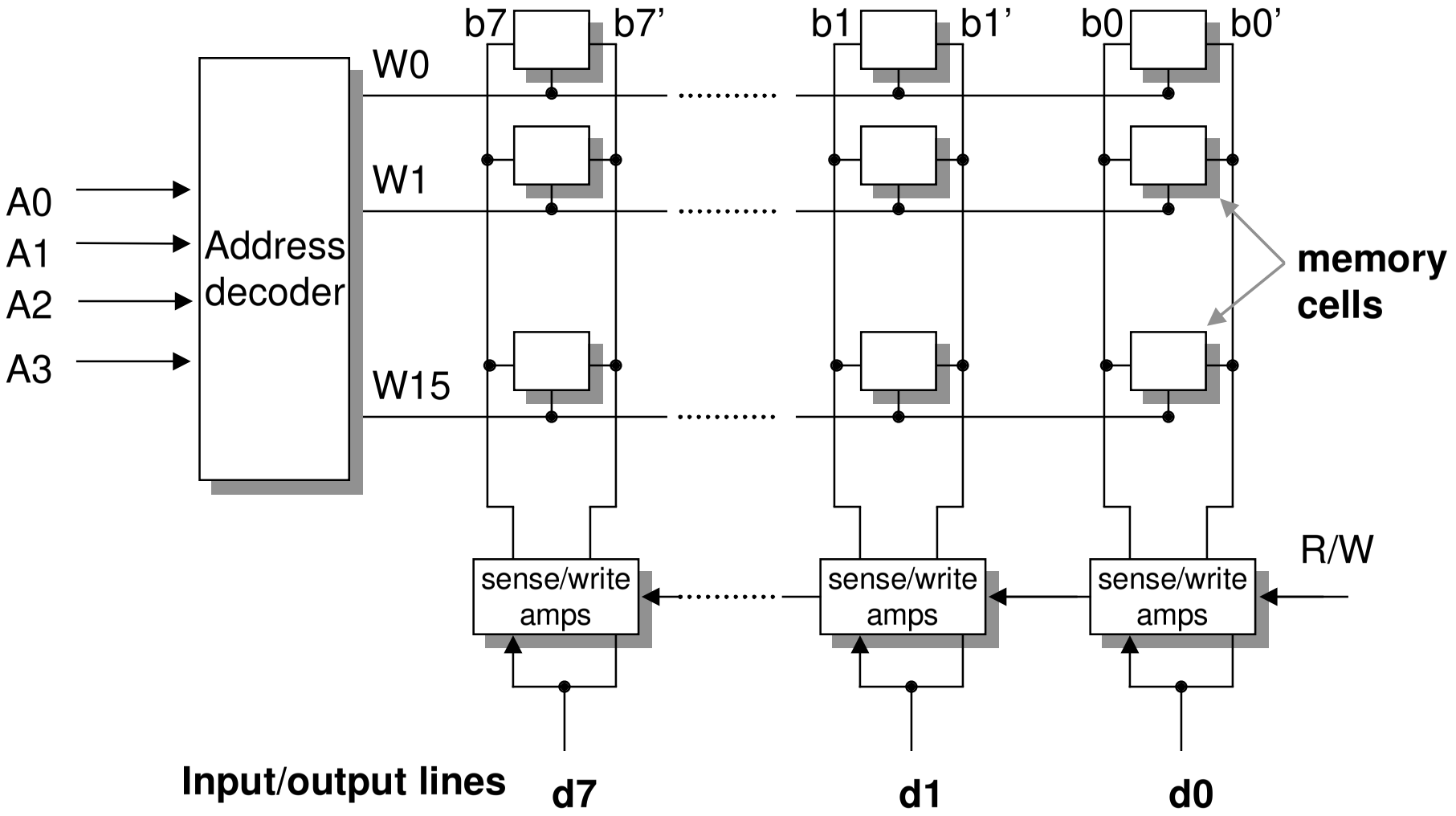
Stability

- **Require Vin = V2**
- **Stable at endpoints**
  - recover from pertubation
- **Metastable in middle**
  - Fall out when perturbed

Ball on Ramp Analogy



Example SRAM Configuration (16 x 8)



Dynamic RAM (DRAM)

Slower than SRAM

- access time ~70 ns [1995]

Nonpersistant

- every row must be accessed every ~1 ms (refreshed)

Cheaper than SRAM

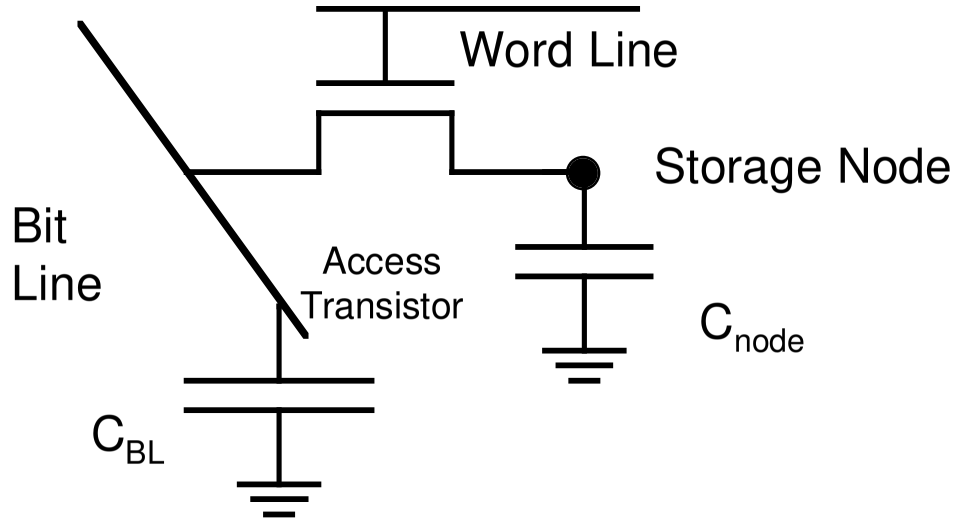
- ~$1.50 / MByte [1998]
- 1 transistor/bit

Fragile

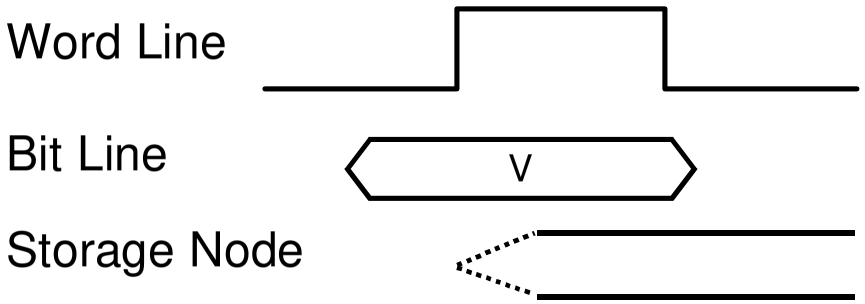
- electrical noise, light, radiation

Workhorse memory technology

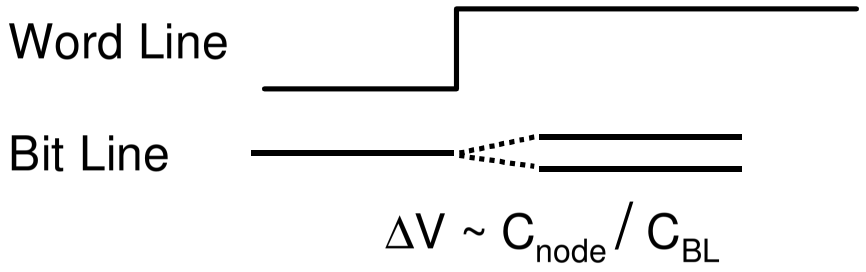
Anatomy of a DRAM Cell



Writing



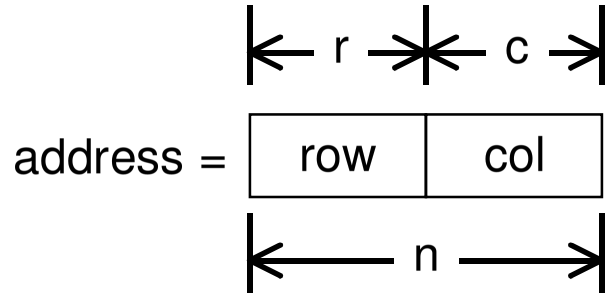
Reading



Addressing Arrays with Bits

Array Size

- **R rows, R = 2^r**
- **C columns, C = 2^c**
- **N = R * C bits of memory**



Addressing

- **Addresses are n bits, where N = 2^n**
- **row(address) = address / C**
  - leftmost r bits of address
- **col(address) = address % C**
  - rightmost bits of address

Example

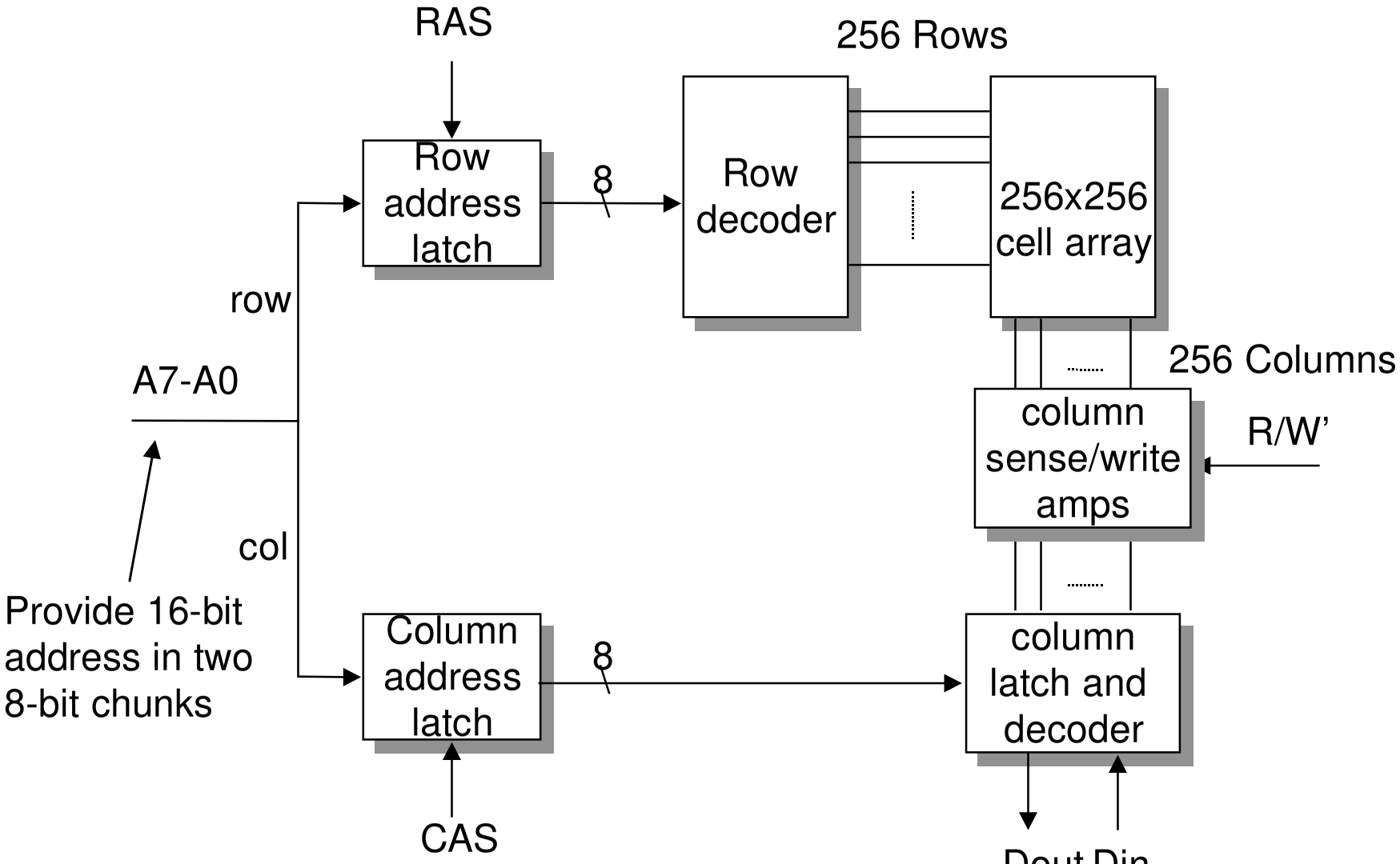
- **R = 2**
- **C = 4**
- **address = 6**

	0	1	2	3
0	000	001	010	011
1	100	101	110	111

row 1

col 2

Example 2-Level Decode DRAM (64Kx1)



DRAM Operation

Row Address (~50ns)

- **Set Row address on address lines & strobe RAS**
- **Entire row read & stored in column latches**
- **Contents of row of memory cells destroyed**

Column Address (~10ns)

- **Set Column address on address lines & strobe CAS**
- **Access selected bit**
  - READ: transfer from selected column latch to Dout
  - WRITE: Set selected column latch to Din

Rewrite (~30ns)

- **Write back entire row**

Observations About DRAMs

Timing

- Access time = 60ns < cycle time = 90ns
- Need to rewrite row

Must Refresh Periodically

- Perform complete memory cycle for each row
- Approx. every 1ms
- Sqrt(n) cycles
- Handled in background by memory controller

Inefficient Way to Get Single Bit

- Effectively read entire row of Sqrt(n) bits

Enhanced Performance DRAMs

Conventional Access

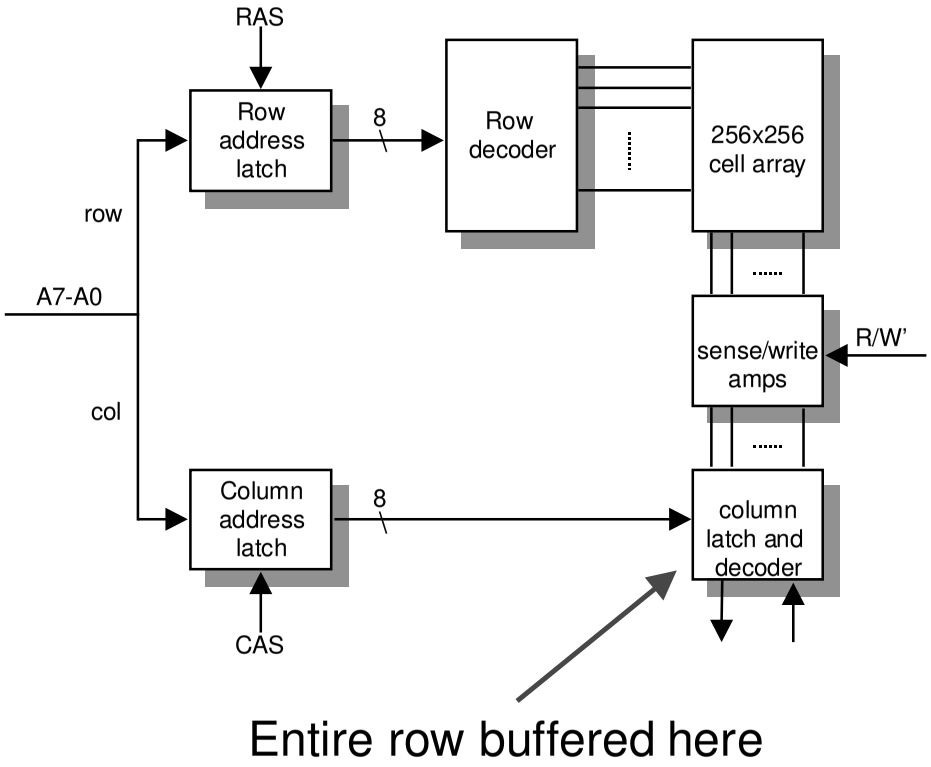
- **Row + Col**
- **RAS CAS RAS CAS ...**

Page Mode

- **Row + Series of columns**
- **RAS CAS CAS CAS ...**
- **Gives successive bits**

Other Acronyms

- **EDORAM**
  - "Extended data output"
- **SDRAM**
  - "Synchronous DRAM"



Typical Performance

row access time	col access time	cycle time	page mode cycle time
50ns	10ns	90ns	25ns

Video RAM

Performance Enhanced for Video / Graphics Operations

- **Frame buffer to hold graphics image**

Writing

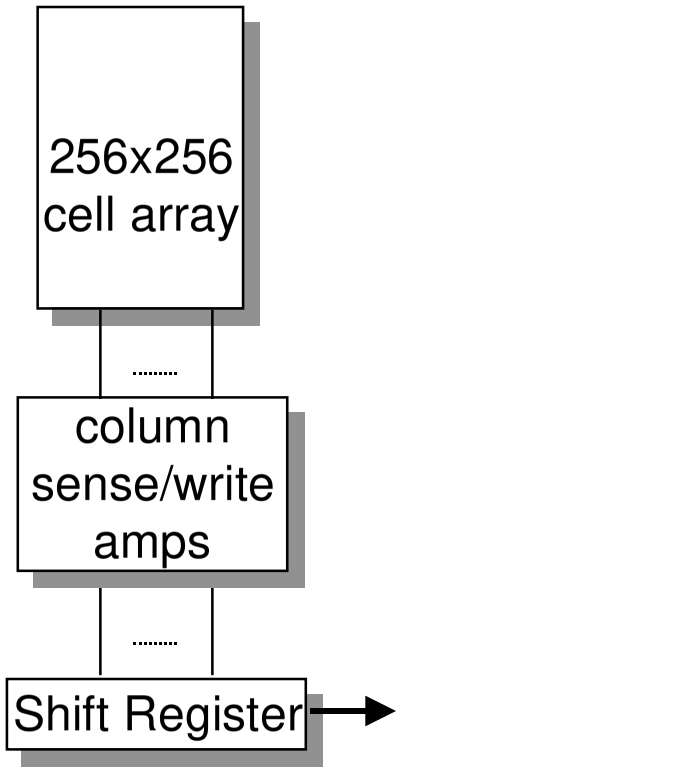
- **Random access of bits**
- **Also supports rectangle fill operations**
  - Set all bits in region to 0 or 1

Reading

- **Load entire row into shift register**
- **Shift out at video rates**

Performance Example

- **1200 X 1800 pixels / frame**
- **24 bits / pixel**
- **60 frames / second**
- **2.8 GBits / second**



DRAM Driving Forces

Capacity

- **4X per generation**
  - Square array of cells
- **Typical scaling**
  - Lithography dimensions 0.7X
    - » Areal density 2X
  - Cell function packing 1.5X
  - Chip area 1.33X
- **Scaling challenge**
  - Typically $C_{node} / C_{BL} = 0.1–0.2$
  - Must keep C_{node} high as shrink cell size

Retention Time

- **Typically 16–256 ms**
- **Want higher for low-power applications**

DRAM Storage Capacitor

Planar Capacitor

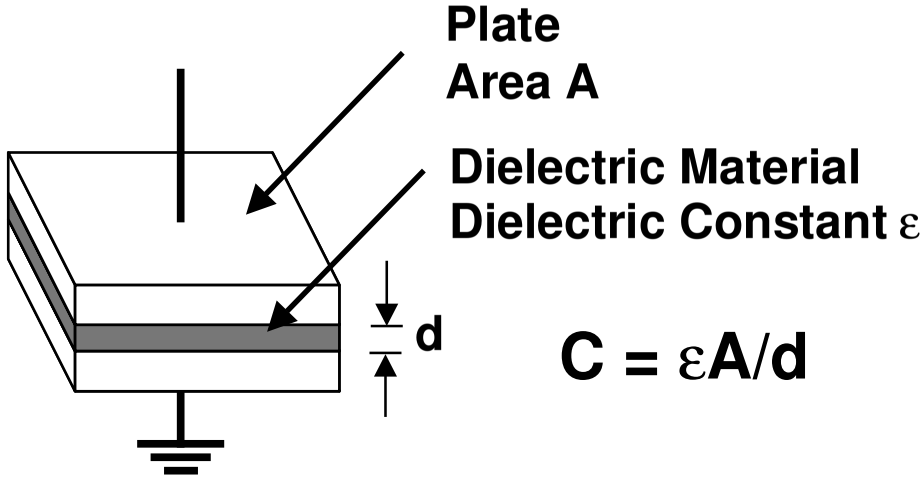
- Up to 1Mb
- C decreases linearly with feature size

Trench Capacitor

- 4–256 Mb
- Lining of hole in substrate

Stacked Cell

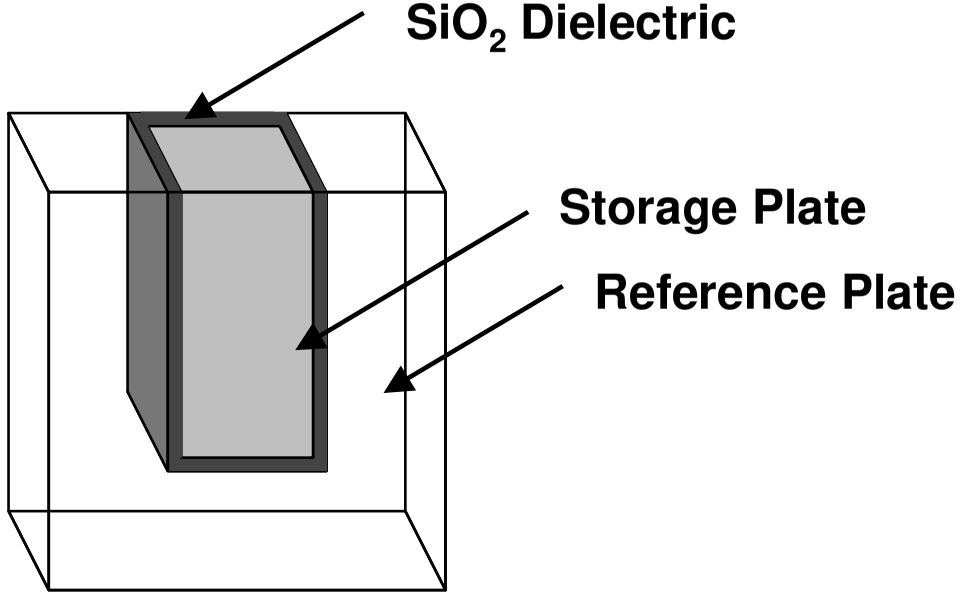
- > 1Gb
- On top of substrate
- Use high ε dielectric



Trench Capacitor

Process

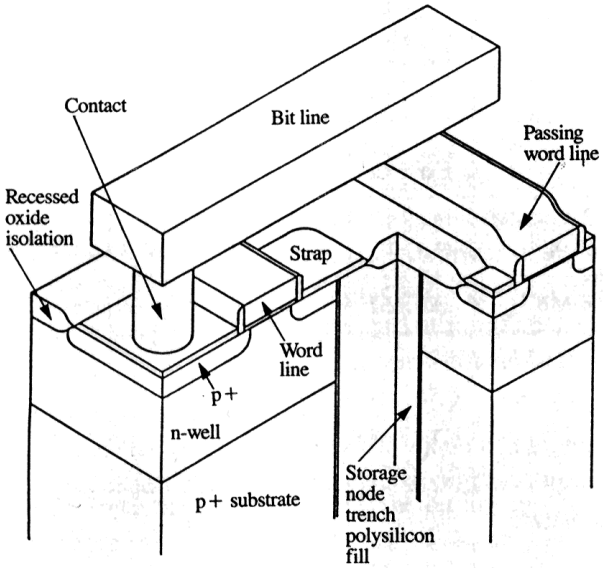
- **Etch deep hole in substrate**
  - Becomes reference plate
- **Grow oxide on walls**
  - Dielectric
- **Fill with polysilicon plug**
  - Tied to storage node



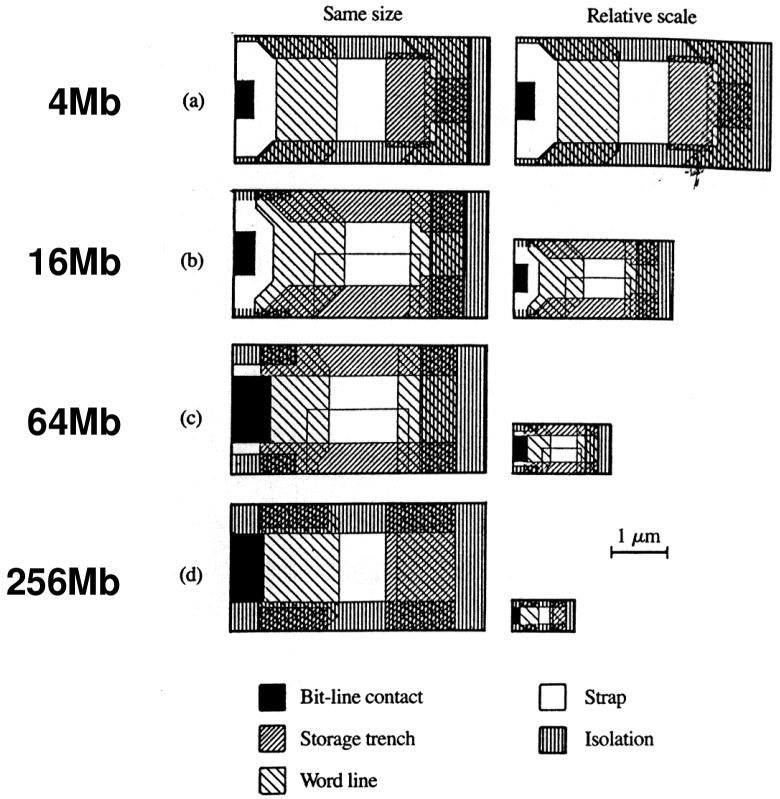
IBM DRAM Evolution

- IBM J. R&D, Jan/Mar '95
- Evolution from 4 – 256 Mb
- 256 Mb uses cell with area 0.6 μm^2

4 Mb Cell Structure



Cell Layouts



Mitsubishi Stacked Cell DRAM

- **IEDM '95**
- **Claim suitable for 1 – 4 Gb**

Technology

- **0.14 μm process**
  - Synchrotron X-ray source
- **8 nm gate oxide**
- **0.29 μm^2 cell**

Storage Capacitor

- **Fabricated on top of everything else**
- **Rubidium electrodes**
- **High dielectric insulator**
  - 50X higher than SiO_2
  - 25 nm thick
- **Cell capacitance 25 femtofarads**

Cross Section of 2 Cells

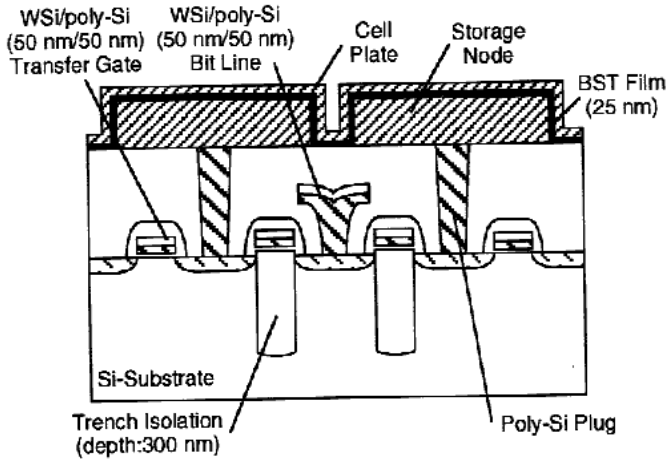


Fig. 2 Schematic cross-sectional view of DRAM memory cells with Ru/BST/Ru stacked capacitors.

Mitsubishi DRAM Pictures

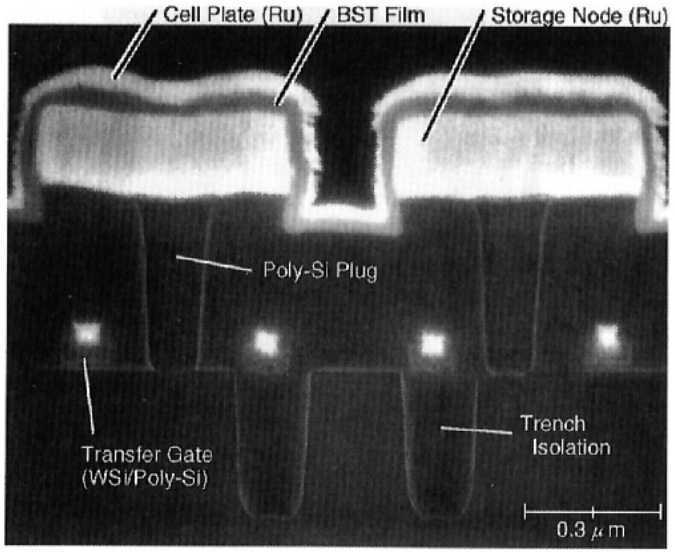


Fig. 3 SEM cross-sectional photograph of the fabricated 0.29-μm² memory cell with Ru/BST/Ru stacked capacitor. The facet was fabricated by focused ion beam etching.

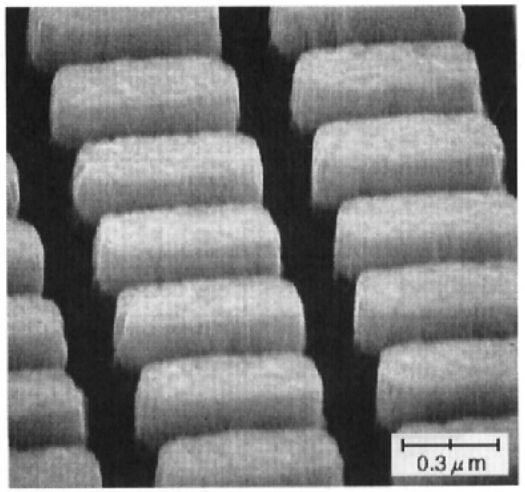


Fig. 8 SEM photograph of a Ru-metal storage node array with a projection … a height of 0.2 μm.

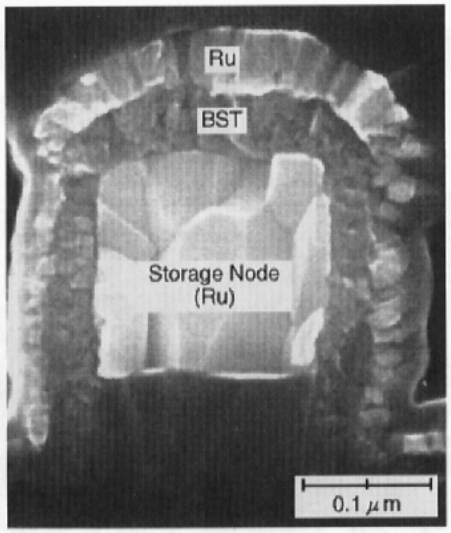
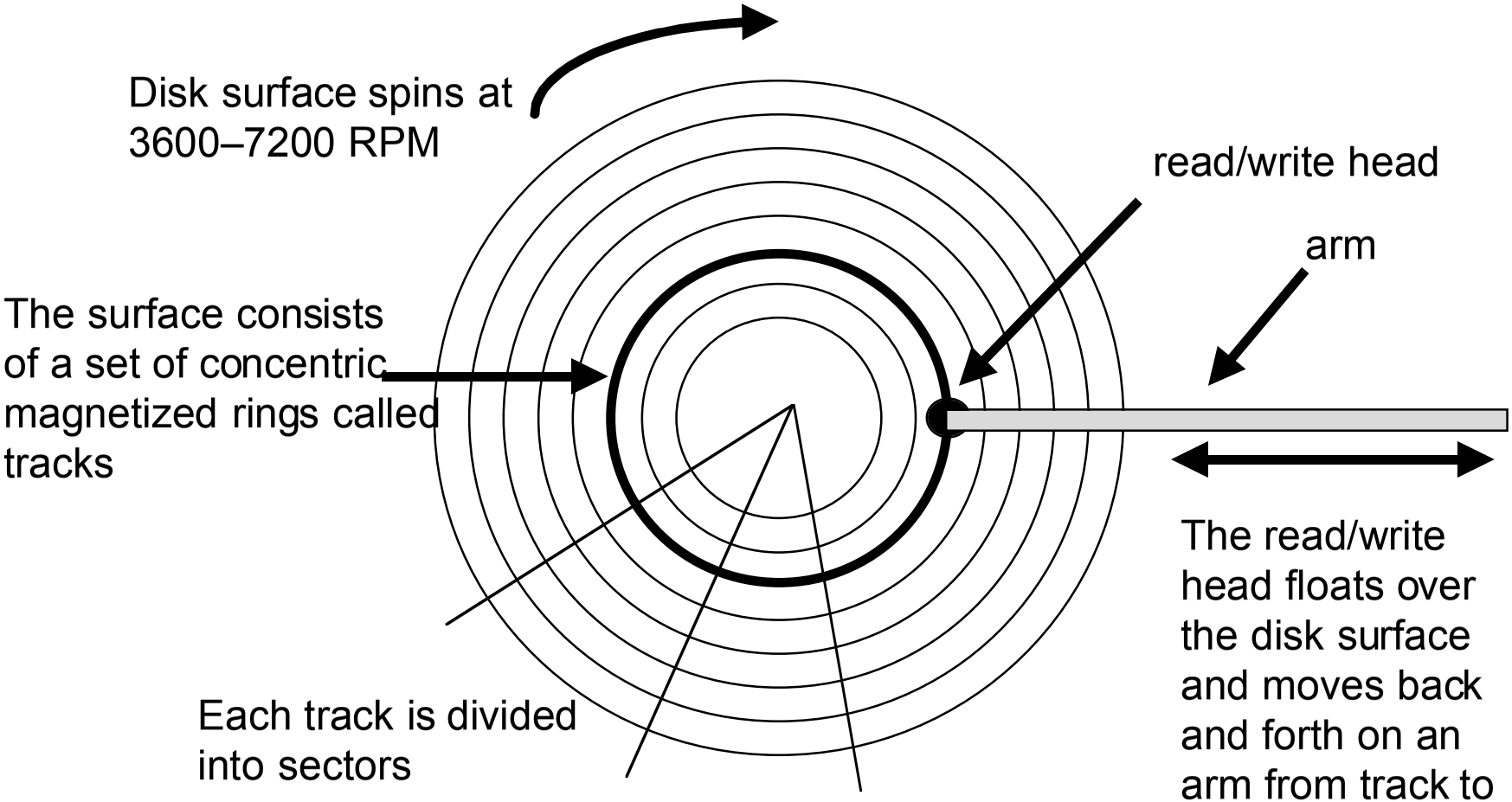


Fig. 10 SEM cross-sectional view of a Ru/BST/Ru capacitor cell. The facet shown is a cleaved facet.

Magnetic Disks



Disk Capacity

Parameter	540MB Example
• Number Platters	8
• Surfaces / Platter	2
• Number of tracks	1046
• Number sectors / track	63
• Bytes / sector	512
Total Bytes	**539,836,416**

Disk Operation

Operation

- **Read or write complete sector**

Seek

- **Position head over proper track**
- **Typically 10ms**

Rotational Latency

- **Wait until desired sector passes under head**
- **Worst case: complete rotation**
  - 3600RPM: 16.7 ms

Read or Write Bits

- **Transfer rate depends on # bits per track and rotational speed**
- **E.g., 63 * 512 bytes @3600RPM = 1.9 MB/sec.**
- **Modern disks up to 80 MB / second**

Disk Performance

Getting First Byte

- **Seek + Rotational latency 10,000 – 27,000 microseconds**

Getting Successive Bytes

- **~ 0.5 microseconds each**

Optimizing

- **Large block transfers more efficient**
- **Try to do other things while waiting for first byte**
  - Switch context to other computing task
  - Interrupts processor when transfer completed

Disk / System Interface

Processor Signals Controller

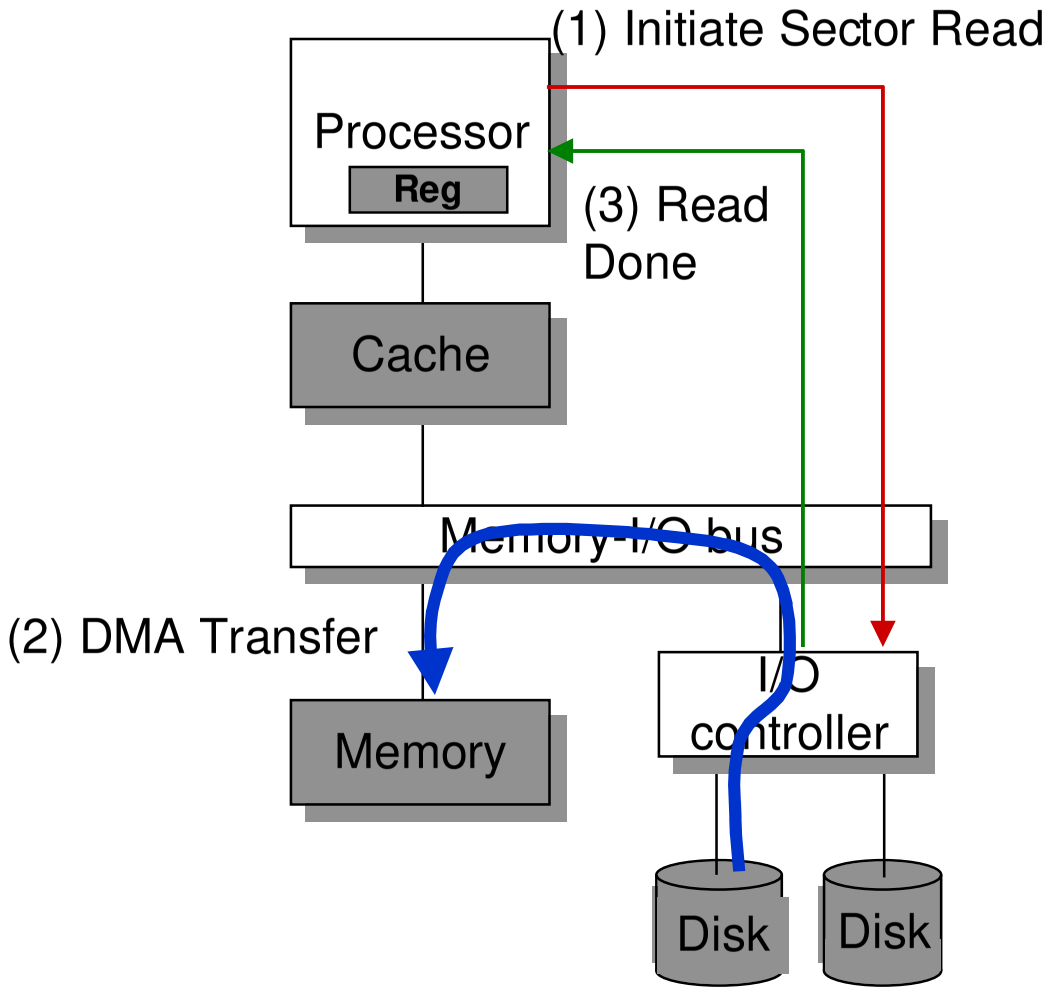
- Read sector X and store starting at memory address Y

Read Occurs

- Direct Memory Access
- Under control of I/O controller

I / O Controller Signals Completion

- Interrupt processor
- Can resume suspended process



Magnetic Disk Technology

Seagate ST-12550N Barracuda 2 Disk

• **Linear density**	**52,187.**	**bits per inch (BPI)**
– Bit spacing	0.5	microns
• **Track density**	**3,047.**	**tracks per inch (TPI)**
– Track spacing	8.3	microns
• **Total tracks**	**2,707.**	**tracks**
• **Rotational Speed**	**7200.**	**RPM**
• **Avg Linear Speed**	**86.4**	**kilometers / hour**
• **Head Floating Height**	**0.13**	**microns**

Analogy

- **Put Sears Tower on side**
- **Fly around world 2.5 cm off ground**
- **8 seconds per orbit**

CD Read Only Memory (CDROM)

Basis

- **Optical recording technology developed for audio CDs**
  - 74 minutes playing time
  - 44,100 samples / second
  - 2 X 16-bits / sample (Stereo)
  - ➡ Raw bit rate = 172 KB / second
- **Add extra 288 bytes of error correction for every 2048 bytes of data**
  - Cannot tolerate any errors in digital data, whereas OK for audio

Bit Rate

- **172 * 2048 / (288 + 2048) = 150 KB / second**
  - For 1X CDROM
  - *N* X CDROM gives bit rate of *N* * 150
  - E.g., 12X CDROM gives 1.76 MB / second

Capacity

- **74 Minutes * 150 KB / second * 60 seconds / minute = 650 MB**

Storage Trends

SRAM

metric	1980	1985	1990	1995	1995:1980
$/MB	19,200	2,900	320	256	75
access (ns)	300	150	35	15	20

DRAM

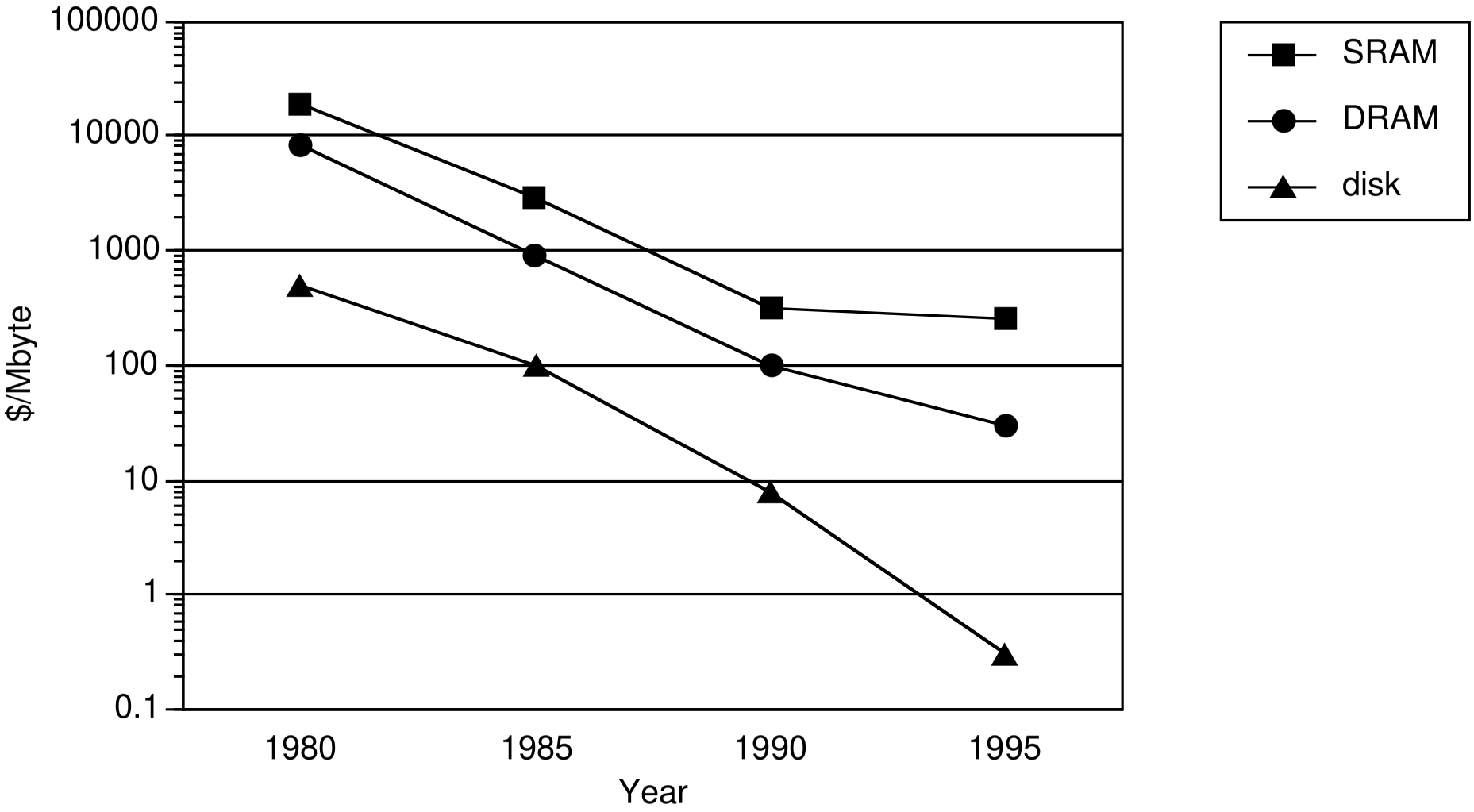
metric	1980	1985	1990	1995	1995:1980
$/MB	8,000	880	100	30	266
access (ns)	375	200	100	70	5
typical size(MB)	0.064	0.256	4	16	250

Disk

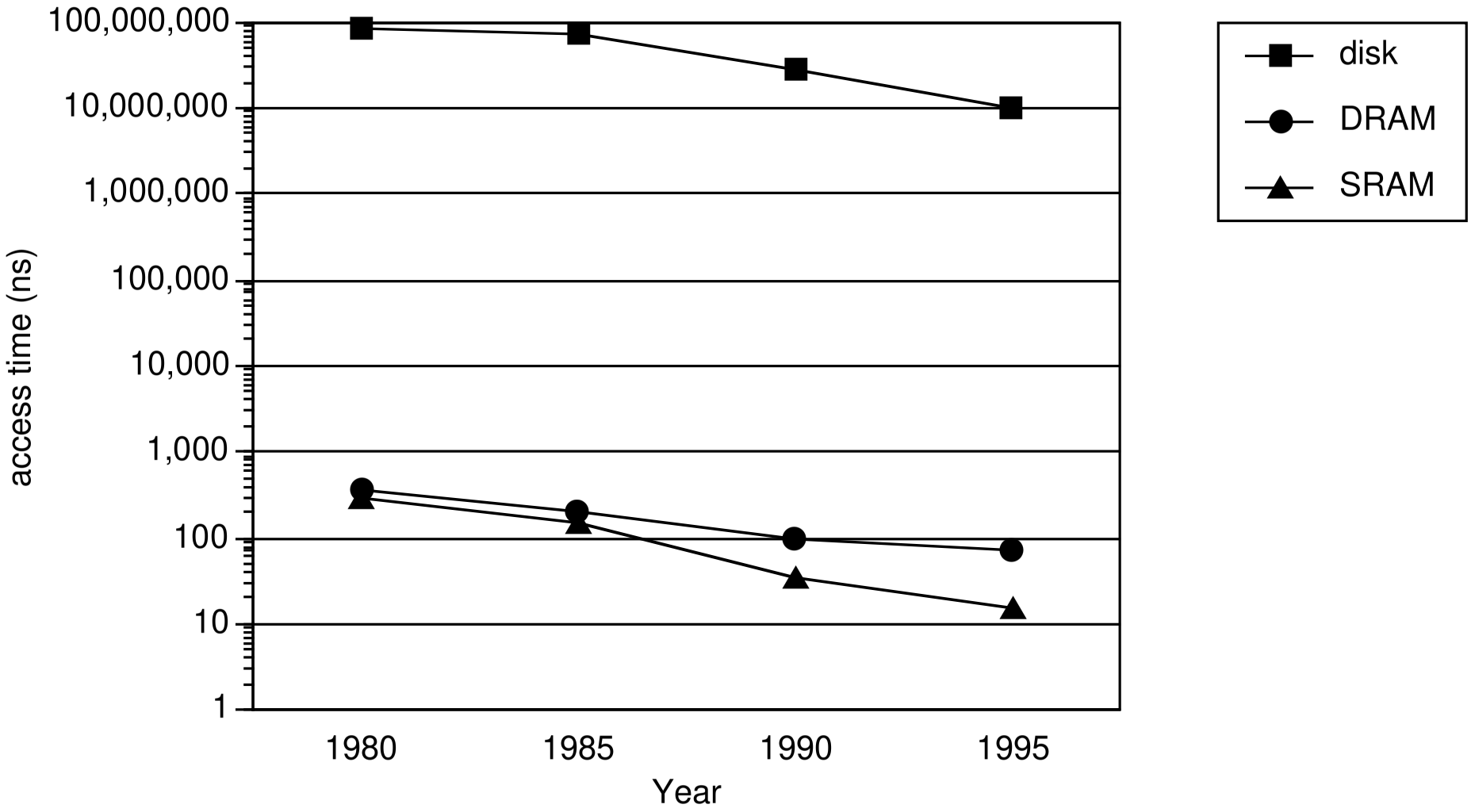
metric	1980	1985	1990	1995	1995:1980
$/MB	500	100	8	0.30	1,600
access (ms)	87	75	28	10	9
typical size(MB)	1	10	160	1,000	1,000

Culled from back issues of Byte and PC Magazine

Storage price/MByte



Storage access times



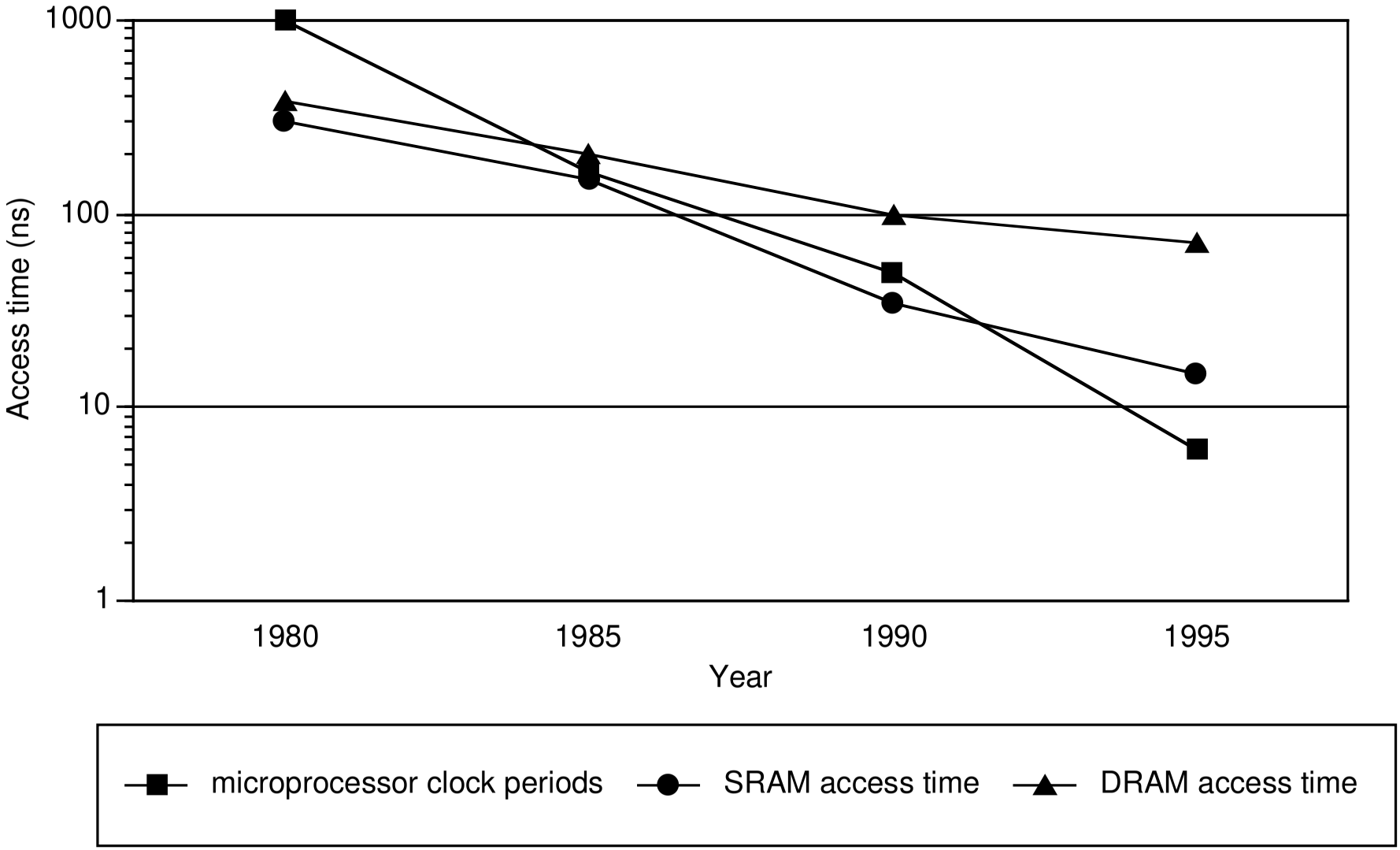
Processor clock rates

Processors

metric	1980	1985	1990	1995	1995:1980
typical clock(MHz)	1	6	20	150	150
processor	8080	286	386	pentium	

culled from back issues of Byte and PC Magazine

The widening processor/memory gap



Memory Technology Summary

Cost and Density Improving at Enormous Rates

Speed Lagging Processor Performance

Memory Hierarchies Help Narrow the Gap:

- **Small fast SRAMS (cache) at upper levels**
- **Large slow DRAMS (main memory) at lower levels**
- **Incredibly large & slow disks to back it all up**

Locality of Reference Makes It All Work

- **Keep most frequently accessed data in fastest memory**