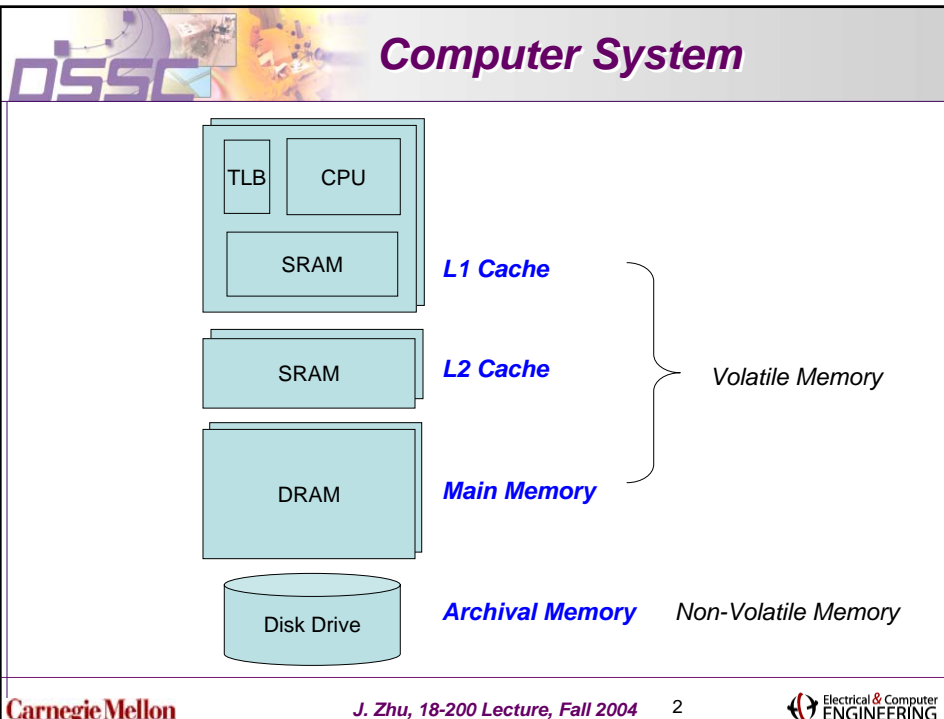# Magnetic Random Access Memory (MRAM)

Jimmy Zhu
ABB Professor in Engineering

Department of Electrical and Computer Engineering
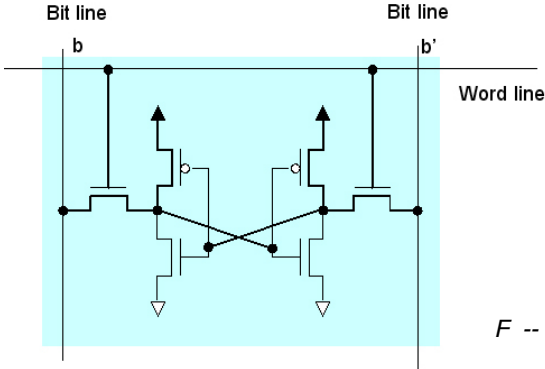*Carnegie Mellon University*

Carnegie Mellon

Computer System

TLB | CPU

SRAM — **L1 Cache**

SRAM — **L2 Cache**

DRAM — **Main Memory**

Disk Drive — **Archival Memory**

Volatile Memory

Non-Volatile Memory

1

Static RAM (SRAM)

Cache Memory

6-Transistor CMOS SRAM

Bit line   Bit line

b   b'

Word line

Fast:

Access time: < 1 ns

= 10^{-9} second

Expensive:

$100 / MByte

Low Density:

>120 F^2

F -- minimum fabrication feature size
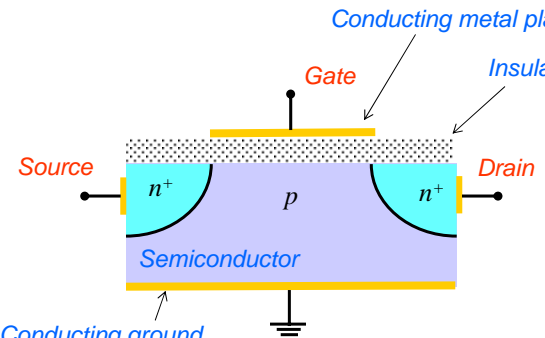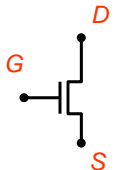
Field Effect Transistor (FET)

Conducting metal plate

Gate

Insulating oxide layer

Source

n^+ p n^+

Drain

Semiconductor

Conducting ground

n-**channel FET**

MOSFET:
Metal-Oxide-semiconductor-FET

D

G

S

symbol

Slide 1

http://www.pbs.org/transistor/science/info/transmodern.html

Active condition:

$$V_{GS} > V_T$$

i.e.

$$V_{GG} > V_T$$

● *electron with charge* $-e$

V_{GG}

i_D

G — *Gate*

Drain

n^+ n^+

S

Source p *D*

R_D

V_{DD}

n**-channel FET**

I_D

Drain current will be a function of gate voltage.

V_{DD}

Slide 2

● *electron with charge* $-e$

Cutoff condition:

$$V_{GS} < V_T$$

V_T *threshold voltage*

G — *Gate*

S

n^+ n^+

$$V_D = V_{DD}$$

Source p *Drain*

D

R_D

V_{DD}

No current

Zero Drain current.

3

A Modern CMOS Process

Gate Oxide
Field Oxide
GATE
N+ N+
Source / Drain Regions
P-Type
Field Oxide

V_{DD}
$M2$
V_{in}
V_{out}
$M1$

gate-oxide

TiSi$_2$ AlCu

SiO$_2$

Tungsten

poly

p-well   n-well   SiO$_2$

n+   p-epi   p+

Dual-Well Trench-Isolated CMOS Process

Dynamic RAM

Main Computer Memory

- *Individual access time 60 ns*
- *10 F²*
- *$4 /MByte*
- *All "1"s need to be refreshed every 1 ms.*

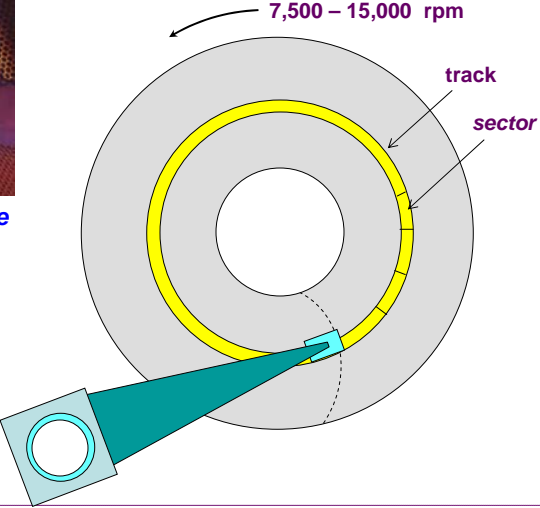State "1" $V = \dfrac{Q}{C}$

State "0" $V = 0$

Bit line

Word line

Poly-silicon word line

Metal bit line

Source and Drain regions

Trench capacitor

Rotational Latency

Inexpensive: $0.001/1MByte

7,500 – 15,000 rpm

track

sector

Rotational Latency

- *Average latency: 3 – 6 ms*

- *Wait until desired sector passes under head*

- *Worst case: a complete rotation*
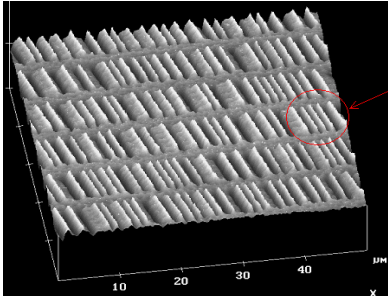 *7,500 rpm = 8 ms*
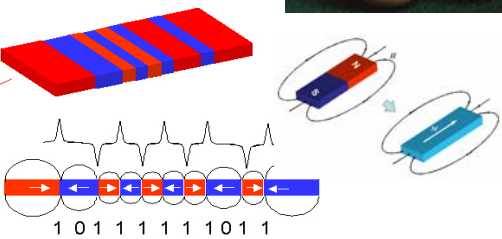 *15,000 rpm = 4 ms*

Hard Disk Drives

18-316   Introduction to Data Storage

18-517   Data Storage Systems Design

Magnetic Force Microscopy Image of A Disk Surface

1 0 1 1 1 1 1 1 0 1 1

Price vs. Speed

Price Per MByte ($) vs. Access Time (second)

- SRAM — 100, 1E-9
- DRAM — ~4, ~7E-8
- HDD — 1E-3, 1E-3

Computer System on a Chip?

Can one change the disk drive into a high speed memory chip?

If one can, one can put the entire computer system on a single chip:
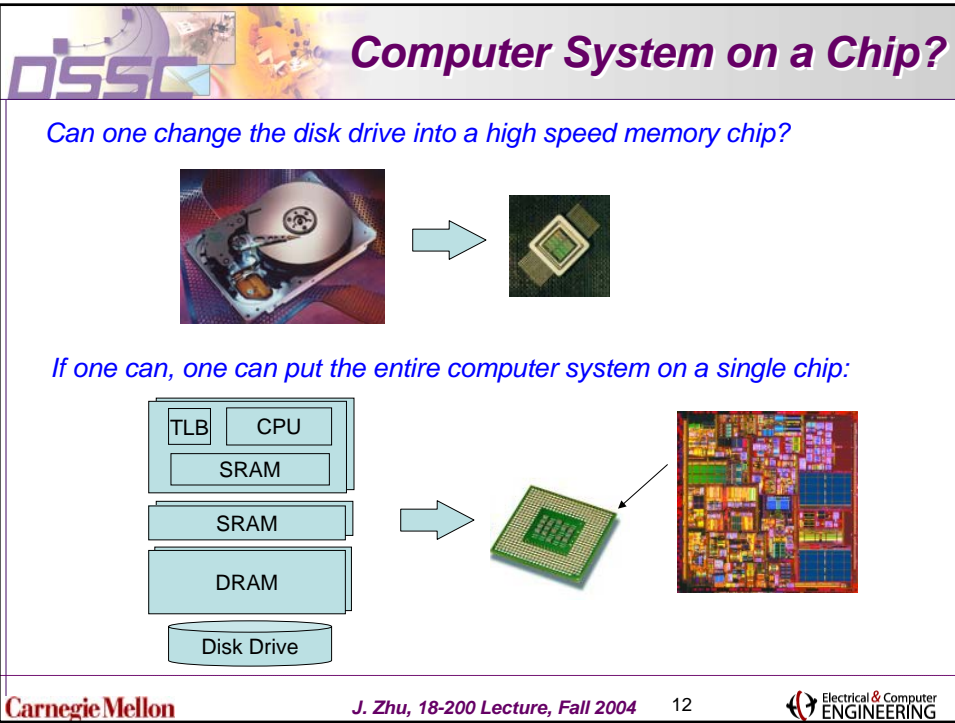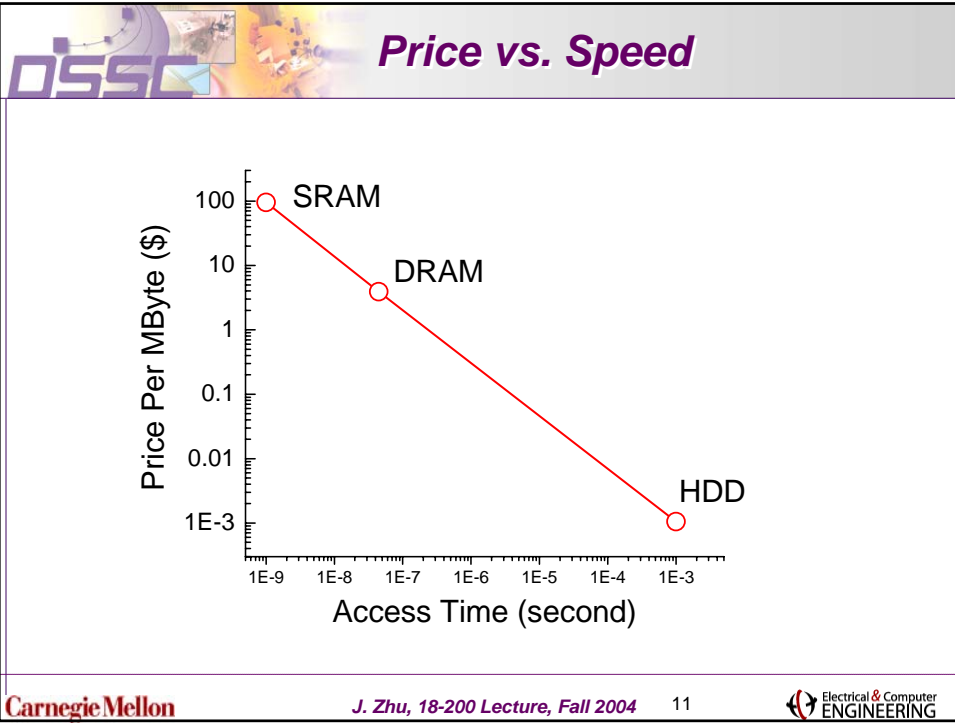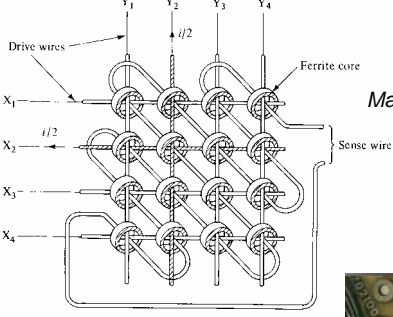
- TLB CPU
- SRAM
- SRAM
- DRAM
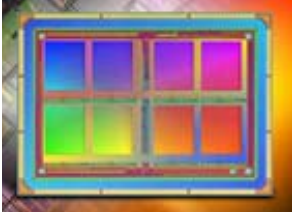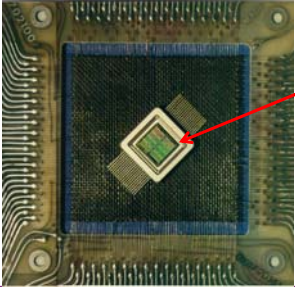- Disk Drive

Motorola
4Mbits MRAM Chip
Magnetic tunnel junction
2003

Honeywell
16Kbits MRAM Chip
AMR Technology 1994

Control Data Corp.
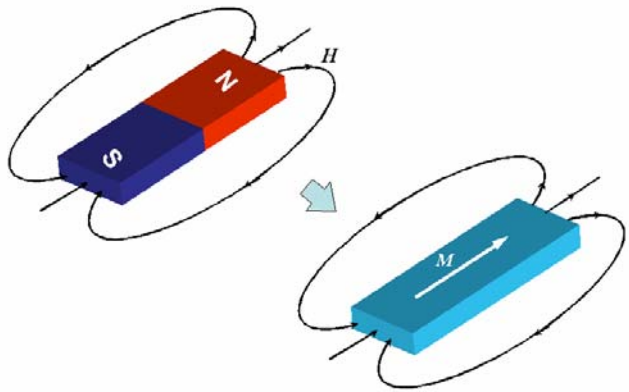1Kbits Ferrite Core Memory
1965

Remember Magnet !

Magnetic moment can maintain its direction without power !
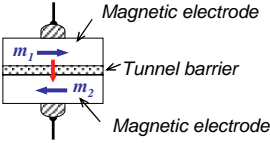
7
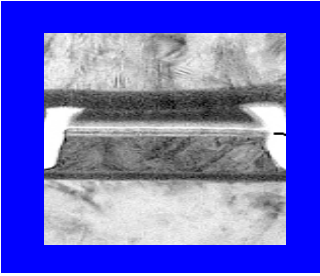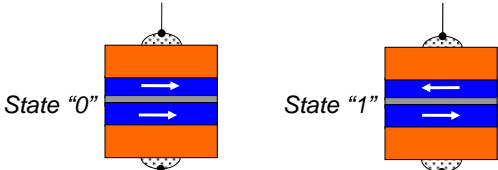
Memory Element

Magnetic Tunnel Junction (MTJ)

Magnetic electrode
m_1
Tunnel barrier
m_2
Magnetic electrode

$CoFe/Al_2O_3\,(7\text{-}20Å)/Co$

State "0"   State "1"

Resistance (kΩ)
Data Bits
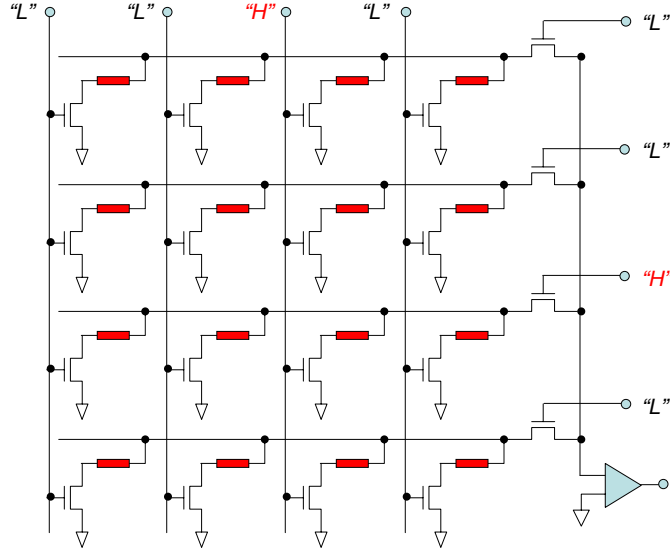
Memory Array

"L"   "L"   "H"   "L"   "L"

"L"

"H"

"L"

8

Detailed Structure

State "0"   State "1"

storage layer
Al$_2$O$_3$ tunnel barrier layer
reference layer
Ru 8Å
flux compensation layer
antiferromagnetic layer

Magnetic
moments
are fixed.

Only the magnetic moment of a storage layer is switched back and forth.
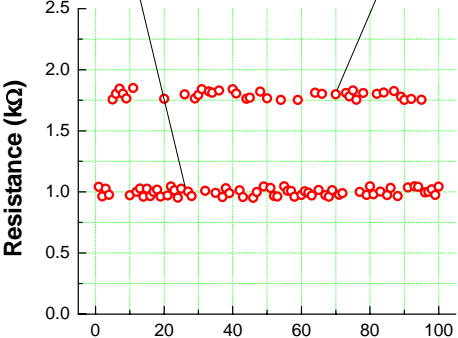
Writing Bits

State "0" ⊙ I   State "1" ⊗ I

$\vec{M}$ $\vec{M}$

I

$\vec{H}$

State "1"

M

H

State "0"

9

X-Point Addressing

$$H_k^{2/3} = H_x^{2/3} + H_y^{2/3}$$

half-select elements

Transistor for read addressing

$I_{write, y}$

$I_{write, x}$

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MRAM Cell

Bit Cell

MTJ

Bit Line

Digit Line

Word Line

Ground line

Silicon Substrate

M1-3   Via   M4   BC   MTJ   M5

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Freescale *4Mbits MRAM Chip*

MRAM: Dream Memory?

Advantages of MRAM:

- ✓ **Nonvolatile** *(No power needed to maintain memory states)*
- ✓ **SRAM Speed** *(~ 1 nanosecond)*
- ✓ **DRAM Density** *(~ 20 F^2)*
- ✓ **Endurance** *(Infinitely rewritable)*

MRAM has the potential to be an universal memory to replace SRAM, DRAM, FLASH, and disk drives in some applications to become the

Universal Solid-State Memory!

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A Potential Game Changer

If MRAM replaces SRAM, DRAM or even disk drives:

➤ *Instant on systems: No booting from disk drive*

➤ *Minimum stand-by power (Turn it off!)*

➤ *Enable computer system to be integrated on a single chip!*
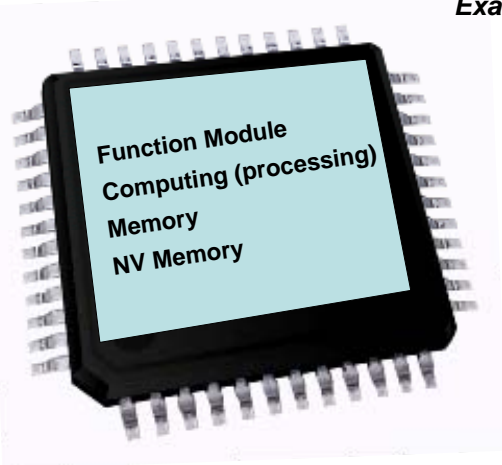
Applications
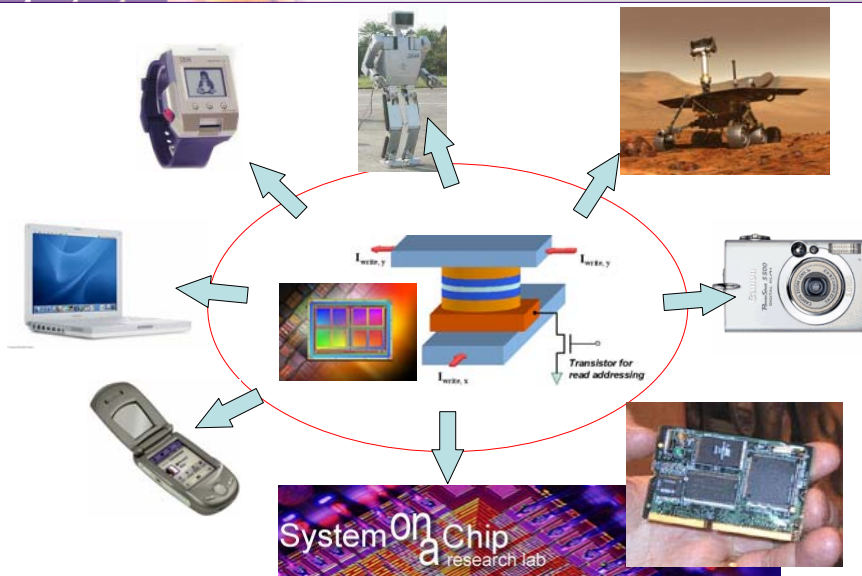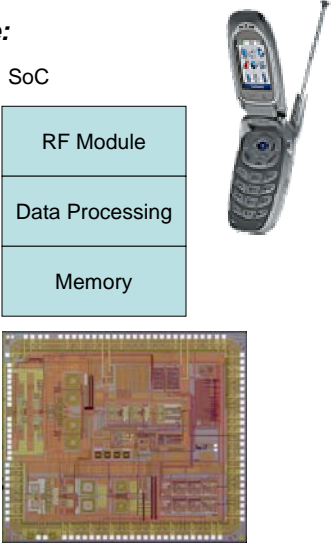
System on Chip (SoC)

Example:

SoC

| RF Module |
| Data Processing |
| Memory |
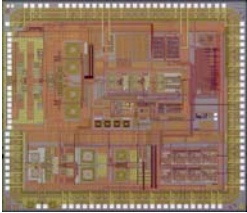
Function Module
Computing (processing)
Memory
NV Memory

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MRAM: Dream Memory?
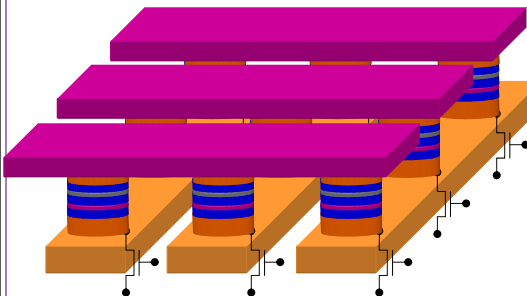
Present MRAM Technology Shortfalls:
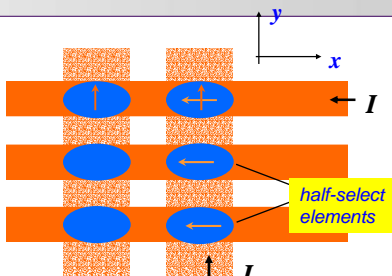
- *Relatively high power dissipation* (high current)

- *Down-size scaling not clear* (thermal magnetic stability)

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ENGINEERING

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X-Point Addressing

$$H_k^{2/3} = H_x^{2/3} + H_y^{2/3}$$
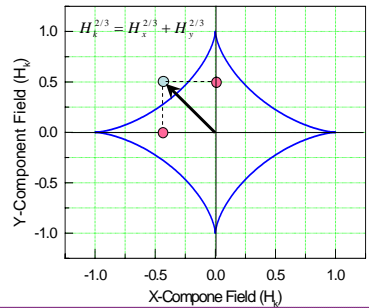
99.999% of power is dissipated as I^2R on the write lines!

half-select elements

Y-Component Field (H_y)

X-Compone Field (H_x)
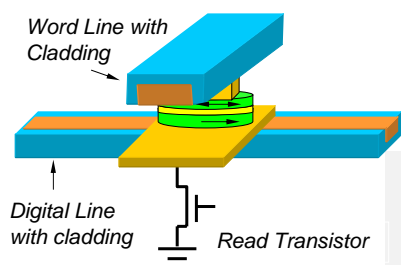
Magnetic Cladding
(18-303 Electromagnetics)
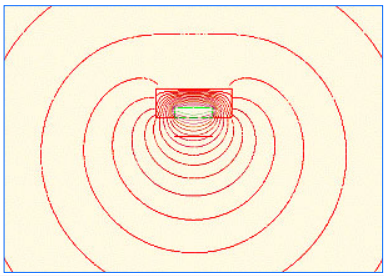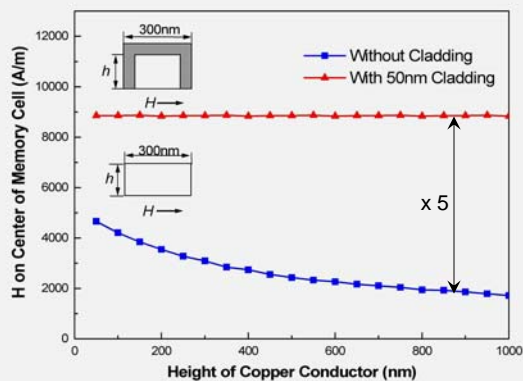
Word Line with Cladding

Digital Line with cladding

Read Transistor

➤ **The main power consumption arises from the ohmic dissipation, I^2R, in word/digital lines.**

H on Center of Memory Cell (A/m)

300nm

Without Cladding
With 50nm Cladding

x 5

Height of Copper Conductor (nm)

14

Thermally Activated Reversal

$0.1\ \mu m$

$0.2\ \mu m$

$H_x = 0.8 H_x^0$

H_x

$\tau_{rise} = 0.3\ ns$

$2\ ns$

t

E

$Angle$

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The Potential Universal Memory

	SRAM	DRAM	Disk Drive	FLASH	MRAM
Speed					
Density					
Cyclability					
Cost					
Non-volatility					
Power consumption					

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Conclusions

MRAM: *The enabling technology for computer systems on a single chip!*

Only Continued Innovation Will Ensure Future Competitiveness of MRAM

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Data Storage Systems Track

Fundamentals of E.E.

18-220

Eng. Electromagnetics

18-303

Intro. to Data Storage Tech.

18-316

18-396

Signal & Sys.

18-517

Data Storage Sys. Design

Physics of Appl. Magn. 18-715

Advanced Appl. Magn. 18-716

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18-517
Data Storage Systems Design

Building a Virtual Disk Drive using MATLAB/SIMULINK

Data to be recorded

Retrieved signal

Equalizer

Recovered data

Detector

18-315 Fall 2004

Introduction to Optical Communication Systems

Professor Jimmy Zhu

jzhu@ece.cmu.edu

Course Objective:
Provide a basic understanding of present optical communication systems and components, as well as future engineering challenges.

Bandwidth Explosion

Source: Agilent Technologies

Data Rate Capacity (bits/second) vs Year

1P, 100T, 10T, 1T, 100G, 10G, 1G, 100M, 10M, 1M, 100k, 10k, 1k, 100, 10, 1

Video on demand — O.S.

Voice-centric Network — World wide web — DWDM, WDM

Doubles every 4.7 years

Coax — Fiber

Data-centric Network (Optical)

Telephone — Doubles every 9 months

Telegraph

1850 1900 1950 2000 2050

Year

3G
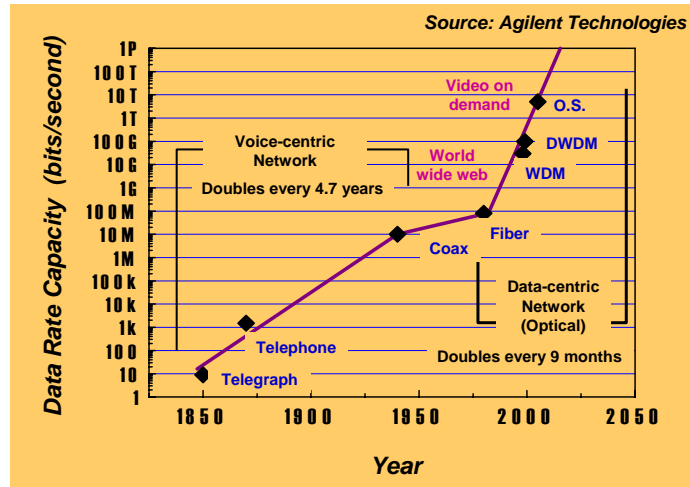
Facts

A single optical fiber is capable of transmiting 2×10^{12} bits of data per second, which is equivalent to

simultaneously carry more than 30,000,000 phone conversations, or

200,000 users download (upload) information at 10 Mbits/second data rate at same time, or

download all 380 CDs (each with 1 hour long music) in 1 second , or

download 30 DVD movies in 1 second .

Present dense wavelength division multiplexing (DWDM) technology is realizing the full potential of a single optical fiber !

A optical fiber cable may contain up to 200 fibers.

Fiber-Optical Long-Haul Routes

Source: KMI

NORTH AMERICAN FIBEROPTIC LONG-HAUL ROUTES PLANNED AND IN PLACE

TERRESTRIAL AND UNDERSEA FIBEROPTIC ROUTES PLANNED OR IN PLACE

WORLDWIDE UNDERSEA FIBEROPTIC ROUTES PLANNED AND IN PLACE

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Metro Optical Network

Source: Nortel Networks
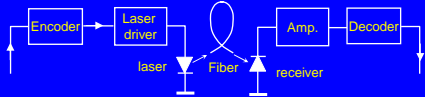
e.g. 10 Gbits Ethernet

Fiber

The optical wireless solution consists of a mesh network of short optical links that extend the fiber loop wirelessly to buildings outside the established fiber network.

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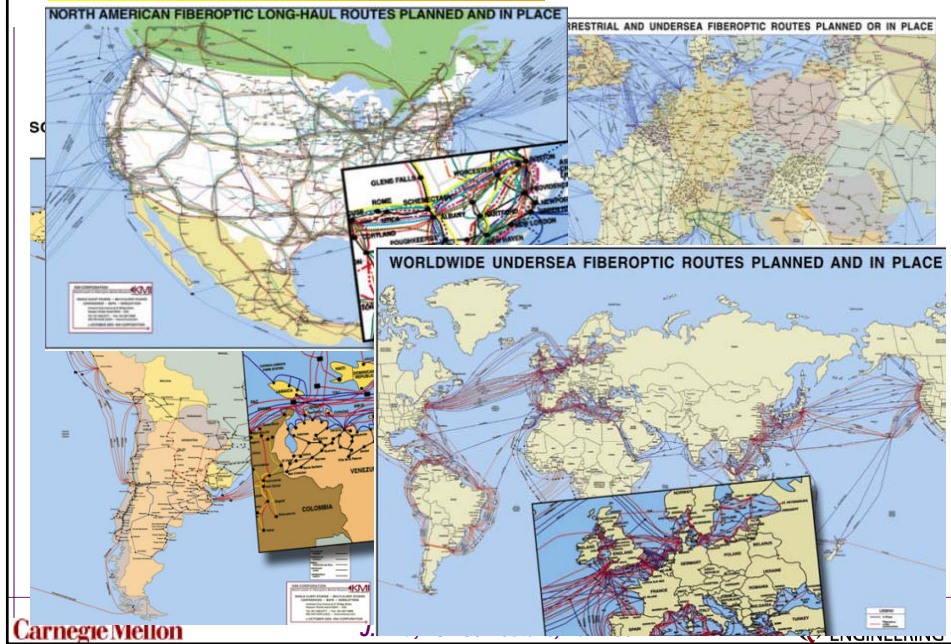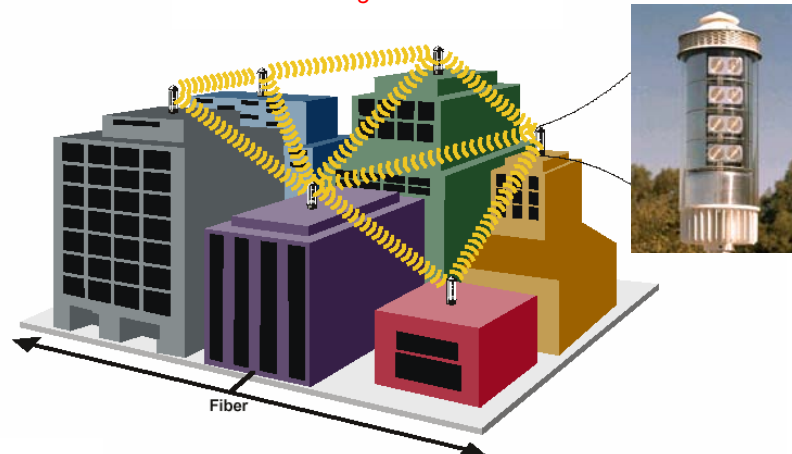*18-315   Introduction to Optical Communication Systems*

Course Coverage

- *Light*
  - ✓ *How light carries information*
  - ✓ *Generation of light*
  - ✓ *Light traveling in a fiber*
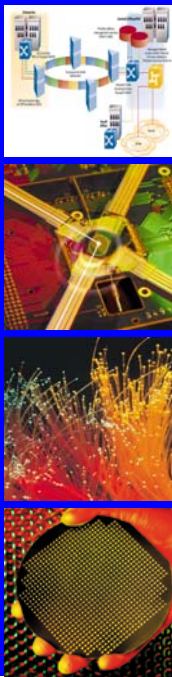 - ✓ *Amplification of Light*

- *Systems*
  - ✓ *Time Division Multiplexing (TDM)*
  - ✓ *Wavelength Division Multiplexing (WDM)*
  - ✓ *Optical networks*

- *Devices and Components*
  - ✓ *Fiber*
  - ✓ *LED*
  - ✓ *Semiconductor lasers*
  - ✓ *Fiber Amplifiers*
  - ✓ *Optical receivers*
  - ✓ *Optical modulators*
  - ✓ *Optical couplers and switches*

Encoder | Laser driver | laser | Fiber | receiver | Amp. | Decoder

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Careers

This course is designed to:

- ► *prepare students with up-to-date education ready for the optical communication and network industry.*

- ► *Provide students sufficient background knowledge for further career development in optical communication systems and networks.*

- ► *Stimulate students' ability for innovation.*

- ► *Train students' problem analyzing and problem solving abilities.*

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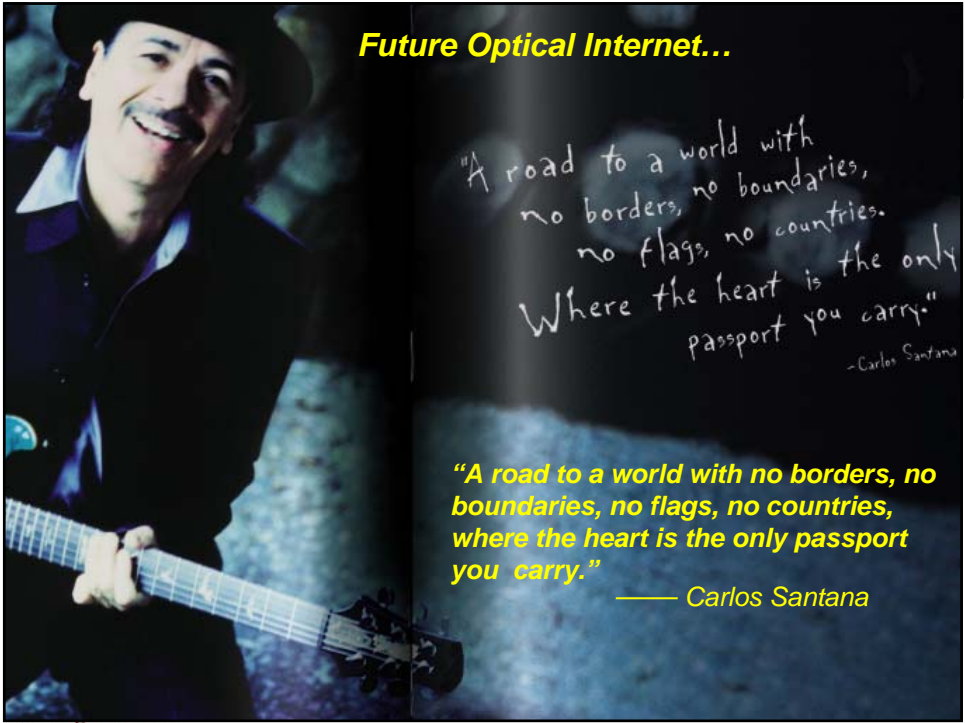
Future Optical Internet…

"A road to a world with no borders, no boundaries, no flags, no countries, where the heart is the only passport you carry."
—— *Carlos Santana*