magnetic information storage

IBM 350 RAMAC, the first hard disk it stored about 4.4Mb

wikipedia.org - “RAMAC”
what do I mean by magnetic recording?
what do I mean by magnetic recording?
what do I mean by magnetic recording?

hard disks.

mostly hard disks.
why do we use hard disks?

what is their role in a computer?

benefits?

disadvantages?

and the real reason .. $$$
basic PC architecture

- access time
- latency

vs.

- volatility
- cost / GB
basic PC architecture

- access time
- latency
- cost / GB
- volatility

CPU
basic PC architecture
basic PC architecture

- CPU
- caches
- SRAM / DRAM

Arrows indicate:
- Access time
- Latency
- Volatility
- Cost / GB
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk

\[ > \text{access time} \]
\[ > \text{latency} \]
\[ > \text{cost/GB} \]
\[ < \text{volatility} \]
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk
- floppy tape / DVD
- CD-ROM

> access time
> latency

> cost / GB
> volatility
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk
- floppy
tape
- DVD
CD-ROM

\[ \text{access time} \quad > \quad \text{latency} \quad > \quad \text{cost/GB} \quad > \quad \text{volatility} \]
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk
- floppy
tape
- DVD
- CD-ROM

▲ access time ▲ latency

▼ volatility ▼ cost / GB
terminology

RAM
random access memory

ROM
read-only memory

access time & latency?
time between request for info & info returned

$ / GB
primary figure of merit.
most other things can be worked around

nonvolatility?
retains data without power

45nm SRAM die  intel.com
every bit has a role

**cache** - reduce latency to main memory

- small memories close to CPU
- even faster than main memory
- temp storage of frequently accessed items

**SRAM / DRAM** - main memory

- blazingly fast
- relatively large
- volatile!!

**HDD** - mass storage

- higher latency
- enormous capacity
- nonvolatile

removable

- portability
- backup
- large ROM

future paradigm shifts? distributed net storage?

EDSAC / wikipedia.org
the need for hard disks (tech)

volatility of semiconductor memories!
  some sort of nonvolatile storage necessary
  why not just battery backup of SRAM?

cost per GB
  SRAM/DRAM are too expensive
  Flash is too expensive
  cache RAM is more expensive

size & throughput
  higher latency, but bandwidth is huge
  enormous sizes

endurance
  essentially unlimited cycling
  radiation hard

punched cards are nonvolatile
Back in the day, disks were expensive.

Sometimes, we would trick the system into using RAM as a disk to avoid swapping floppies.

now RAM disks make a comeback ...
the need for mass storage (human)

sound
   several MB per minute / lossy
   tens of MB per minute / “lossless”

pictures
   several MB per image

video
   ~ 1 MB per sec
   several GB per movie
   with lossy compression!

data mining
   enormous sizes
some physics of information storage ...
how do hard disks work, more or less?

spinning (~$10^4$ rpm) part holds data. sliding part reads and writes data.
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

Magnetic medium

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

Magnetic medium
Read-write head
Voice-coil actuator

images from M. Coey
160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

- 8 Gbit 1” drive for cameras
- 160 Gbit 2.5” perpendicular drive for laptops

Magnetic medium
Read-write head
Spindle motor
Voice-coil actuator

images from M. Coey
media basics

Hard disk
- tiny magnetized regions
- direction (N/S) stores bit
- magnetic sensor reads bits

LP records
- tiny bumps
- needle moves

CDs
- pits store bits
- optical reflectivity
media basics

hard disk platters are round.

so how is data arranged?

*tracks* = concentric circles

*sectors* = wedge of a track

sector has fixed # bytes
media basics

CoCrPt alloy
platters - Al or glass substrate
typical magnetic region
  ~200-250 nm wide, ~25-30 nm down-track
  100 billion bits (Gigabits) per in²

mfm image
sees transition field

reading and writing basics

(longitudinal recording)

sensor - magnetoresistive

reading and writing basics

...(perpendicular recording)...

soft underlayer becomes part of the flux guide
...careful concentration of flux...
read head (and its reflection)
positioning basics

- current powers voice coil†
- field generated moves head L or R
- more precise than stepper motor

† this is the same way a speaker cone moves
positioning basics

• current powers voice coil†
• field generated moves head L or R
• more precise than stepper motor

† this is the same way a speaker cone moves
why magnets?

magnetic view

magnets remember their state
once magnetized, they stay that way

with a little bit of energy, we can control them
switch from N to S
why magnets?

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once magnetized, they stay that way
with a little bit of energy, we can control them
switch from N to S
why magnets?

what happens when you break a magnet? you get two magnets

now: do this 25 more times

\[\rightarrow 33 \text{ million magnets, all } 50\text{nm across}\]

about 1,000 times thinner than a hair

we can make really tiny magnets

smaller is better, to a point
technology timeline

In-plane

1960

RAMAC - first hard-disc drive; inductive head

1970

TMR discovered

1980

GMR discovered

1990

AMR head

2000

Spin-valve head (CIP)

2010

TMR head

1950

AMR discovered

(1857)

images and text from M. Coey
technology timeline

- **1955**: 40 Mb, 50x2, 24”, 1200 rpm
- **2005**: 160 Gb, 1, 2.5”, 18000 rpm

Images and text from M. Coey
areal density vs. DRAM
The incredible shrinking bit! 
Predicted relative sizes of HDD storage bits

(assumes areal densities continue to double yearly)
The incredible shrinking bit!
Predicted relative sizes of HDD storage bits

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The incredible shrinking bit!
Predicted relative sizes of HDD storage bits

(assumes areal densities continue to double yearly)

2002: 400 nm x 50 nm
2004
2006
2008
2010
2012: 4.4 nm x 4.4 nm
The incredible shrinking bit! Predicted relative sizes of HDD storage bits

(assumes areal densities continue to double yearly)

2002

2004

2006

2008

2010

2012: 4.4 nm x 4.4 nm

this will probably not happen
50 TB per square inch on a quarter …

• over 3.4 million high-resolution photos, or …
• 2,800 audio CDs, or…
• 1,600 hours of television, or …
50 TB per square inch on a quarter ...

- over 3.4 million high-resolution photos, or …
- 2,800 audio CDs, or…
- 1,600 hours of television, or …

- the entire printed collection of the U.S. Library of Congress

Library of Congress

Library of Congress, Jefferson building
so what’s the problem?

at some point, they are no longer stable

heat makes them ‘wiggle’
   like drops of water on a griddle

bits are no longer reliable

so we need stronger magnets ...
   ... which need more field to magnetize
   ... which needs more power

HUGE challenge in nanoscale materials science!

I bit needs $k_B T$ ...
$$\text{vs}$$ flash and DRAM

Diagram: Average Price of Storage over Years 1990 to 2010

- HDD
- DRAM
- Flash
- Paper/Film

Price/MB, Dollars

Year


Ed Grochowski

THE UNIVERSITY OF ALABAMA
price is the real advantage.
price is the real advantage.

flash is beating the 1” HDD in some apps
e.g., mp3, camera
price is the real advantage.

flash is beating the 1” HDD in some apps e.g., mp3, camera

power consumption may be the larger issue
power consumption is not an advantage

latency ...

fundamental limits of magnetism & thermal stability?
SO!

how does flash work?

how about RAM?
the basics of Flash

**NOR Cell**

- $V_G < 0$ channel pinched
- $V_G > 0$ channel open

- Like a MOSFET
- Uses 2 gates

- Control gate
- Floating gate
- Source: $n^+$
- Channel
- Drain: $n^+$
- P substrate
- Tunnel oxide
- Isolation oxide
"hot electron injection"

- ~7V to drain
  - pull $e^-$ through channel
- ~12V to control gate / open channel
  - injects $e^-$ into floating gate through tunnel oxide
- floating gate now charged
writing

“hot electron injection”

• ~7V to drain
  pull e\(^-\) through channel
• ~12V to control gate / open channel
  injects e\(^-\) into floating gate through tunnel oxide
• floating gate now charged
writing

“hot electron injection”

- ~7V to drain
  pull e\(^-\) through channel
- ~12V to control gate / open channel
  injects e\(^-\) into floating gate through tunnel oxide
- floating gate now charged
writing

“hot electron injection”

- ~12V to control gate / open channel
  - injects e⁻ into floating gate through tunnel oxide
- ~7V to drain
  - pull e⁻ through channel

• floating gate now charged
writing

“hot electron injection”

• ~12V to control gate / open channel
  injects e⁻ into floating gate through tunnel oxide
• floating gate now charged

• ~7V to drain
  pull e⁻ through channel
writing

“hot electron injection”

- ~12V to control gate / open channel
  - injects e\(^{-}\) into floating gate through tunnel oxide
- ~7V to drain
  - pull e\(^{-}\) through channel
- floating gate now charged
erasing

reset all bits to “1”

-9V to control
pinch off channel

~6V to source

suck electrons out of floating gate into source

Fowler-Nordheim tunneling
erasing

reset all bits to “1”

-9V to control
  pinch off channel

~6V to source

suck electrons out of floating gate into source

Fowler-Nordheim tunneling

-9V to control gate

OPEN
erasing

reset all bits to “1”

~ -9V

-9V to control
  pinch off channel
• ~6V to source
• suck electrons out of floating gate into source
  Fowler-Nordheim tunneling
erasing

reset all bits to “1”

-9V

~6V

OPEN

source

drain

control gate

floating gate

• -9V to control
  pinch off channel
• ~6V to source
• suck electrons out of floating gate into source
  Fowler-Nordheim tunneling
reset all bits to “1”

-9V to control
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suck electrons out of floating gate into source

Fowler-Nordheim tunneling
erasing

reset all bits to “1”

-9V

OPEN

control gate

floating gate

source

e- e-

drain

e-

-9V to control
pinch off channel

~6V to source

suck electrons out of floating gate into source

Fowler-Nordheim tunneling
reading

5V to control
1V to drain
floating gate charged = channel is pinched off = “0”
floating gate discharged = channel open = “1”
presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
- floating gate discharged = channel open = “1”

Presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
- floating gate discharged = channel open = “1”

Presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
- floating gate discharged = channel open = “1”

Presence of charge modulates $I_{SD}$!
Floating gate memory reading:

- 5V to control
- 1V to drain
- Floating gate charged = channel is pinched off = "0"
- Floating gate discharged = channel open = "1"

Presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
- floating gate discharged = channel open = “1”
  presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
- floating gate discharged = channel open = “1”

presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
- floating gate discharged = channel open = “1”

Presence of charge modulates $I_{SD}$!
the basics of Flash
the basics of Flash

- no mechanical limitations

- lower latency
  
  = attractive for speed, noise, power consumption, reliability.
the basics of Flash

+ no mechanical limitations

+ lower latency
  = attractive for speed, noise, power consumption, reliability.

- cost/GB still significantly higher (but decreasing rapidly!)

- finite number of erase/write (typically $10^6$ cycles guaranteed)
  unable to support an OS (swap!)
  warranties on flash-based disks trending $\geq$ HDD