Hard Disk Drives

Last updated 3/1/21
Hard Disk Drive

• History
  • Magnetic Tapes
    • Serial access
  • 1955 – First Hard Disk Drive
    • RAMAC – Random Access Method of Accounting Control

100 bits/in – inside track
55 bits/in – outside track
1s average access time
Hard Disk Drive

• History

• Disk Diameter

* Memory Systems, Jacob et. al.
Hard Disk Drive

- History
- Areal Density

Src: InSIC

Src: JAP 117
Hard Disk Drive

• History

• Linear Density

* Memory Systems, Jacob et. al.
Hard Disk Drive

• History
• Units

Src: Forbes
Hard Disk Drive

• Fundamentals

• Rotating Storage Devices
  • Phonograph – record
    • Analog Storage
    • Indentations in plastic
  • CD/DVD
    • Digital Storage
    • Reflectivity of special coating
  • Hard Disk Drive
    • Digital Storage
    • Magnetic Polarization
Hard Disk Drive

• Fundamentals

• Rotating Storage Devices
  • Information is stored in rings around the disk
    • Concentric
    • Spiral
  • Two values locate all information
Hard Disk Drive

• Fundamentals

• Rotating Storage Devices

  • A movable Arm allows access for variable r

  • Rotating Disk allows access to θ
Hard Disk Drive

• Fundamentals

  • Rotating Storage Devices
    • Multiple Disks
    • 2 sided
    • Multiple Read/write heads
Hard Disk Drive

• Fundamentals

• Disk Drive Physical Size

• Physical sizes are determined by the size of the enclosure – not the disk
  • But not really the correct size – e.g. 3.5” drives are 4” wide

• Common Sizes
  • 3.5” – 4” x 5.75” x 1”
  • 2.5” – 2.75” x 3.94” x 0.75” with some low capacity drives as thin as 0.37”

• Less Common Sizes
  • 1.8”, 1”
Hard Disk Drive

• Fundamentals

• Disk Drive Performance
  
  • Response Time - Average
    • Time from command issue to transfer complete
    • Dependent on type of operation
      • R/W, sequential/non-sequential
  
  • Throughput (Bandwidth)
    • Data transfer rate
    • MB/s
  
  • Multiple requests
    • Stored in a command queue
    • Queueing Theory governs performance metrics
Hard Disk Drive

• Physical Layer

• Magnetism
  • Movement of electrons in atoms → moving charge
  • Moving charge → magnetic field

• In most materials
  • Random orientation of atoms
  • Random spin of the electrons
  • → cancelling of all the magnetic fields
Hard Disk Drive

• Physical Layer

• Magnetic Domains
  • Small regions 1mm³
  • Materials with unpaired electrons $\rightarrow$ net magnetic field
  • Micro-structure of the material causes the magnetic fields to align
  • In most materials these domains are random $\rightarrow$ no net magnetism
  • Ferro-magnetic materials
Hard Disk Drive

• Physical Layer

• Ferromagnetism
  • Materials with magnetic domains
  • When an external magnetic field is applied
    • The magnetic fields of the domains align
  • When the external magnetic field is removed
    • The magnetic fields of the domains remain aligned
    • Leaving behind a material that creates a net magnetic field

• The material has been magnetized
Hard Disk Drive

• Physical Layer

• Ferromagnetic Materials

• Magnetization Hysteresis

• Saturation – additional applied magnetic force will not increase the created magnetic field

• Retentivity – remnant magnetization when the external field is removed

• Coercivity – amount of reverse magnetic force required to de-magnetize the material
Hard Disk Drive

- Physical Layer

- Ferromagnetic Materials
  - Curie Temperature
    - Above this temperature the magnetic domains will not remain aligned once the external field is removed
  - Hard magnetic materials have wide hysteresis plots
    - Good for recording media
  - Soft magnetic materials have narrow hysteresis plots
    - Good for recording head materials
  - Easy axis
    - Direction the material prefers to point to
    - Disk want the easy axis to be parallel to the plane of the recording (disk)
Hard Disk Drive

• Writing

  • Saving data in a digital representation

  • Only need to know the direction of the induced magnetic field
    • Define positive and negative in direction of the track

  • Create an external field sufficient to induce saturation
    • Maximizes the Retentivity
    • Only need two values +/-
Hard Disk Drive

• Writing

external magnetic field

Ferromagnetic material
Hard Disk Drive

• Reading

  • Sense the very weak magnetic fields created by the magnetized regions in the material

  • Information is NOT stored in the direction of the magnetization

  • Information is stored in the transitions
    • Transition $\rightarrow 1$ Independent of direction of change
    • No transition $\rightarrow 0$ Independent of the current magnetization direction
Hard Disk Drive

• Reading

• Requires some sort of clock or synchronization

• Writing must be done in blocks
  • No way to just write a bit – need historical information
  • Blocks for write are called sectors
Hard Disk Drive

• Disks

  • Thin – maximize space utilization

  • Light – minimize power required to rotate

  • Rigid – low resonance

  • Flat and Smooth – to allow heads to have fixed height
    • No slapping
    • Consistent R/W characteristics

• Hard magnetic material

  • High retentivity - maximize S/N ratio
  • High coercivity – maximize stability of written data
Hard Disk Drive

• Disks

• Substrate

  • Typically Aluminum or an aluminum alloy
    • Low cost
    • Acceptable but not best in class smoothness
    • Soft – easily damaged

  • For small diameter disks glass or ceramics can be used
    • These can be made very smooth, but can be brittle for larger sizes
Hard Disk Drive

- Disks

- Magnetic Layer
  - Magnetic material composed of grains of magnetic domains
  - Smaller grains
    - Give better areal density
    - Less magnetically stable
  - Gamma ferric oxide, cobalt modified GFO, Chromium Dioxide, Barium ferrite
  - Deposited through thin-film sputtering
    - Allows for thin layers → sharper transitions
Hard Disk Drive

- Disks
  - Ni-P sublayer
    - Harder than AL
    - Allows for better polishing
  - Cr Underlayer
    - Interface for the magnetic coating
    - Better microstructure than Ni-P
  - Magnetic Layer
  - Carbon overcoat
    - Protects the magnetic material from corrosion
    - Prevents scratches and other damage
  - Lubricant
    - Prevent wear between head and disk should they touch

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
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<tbody>
<tr>
<td>Lubricant</td>
<td>1nm</td>
</tr>
<tr>
<td>Carbon Overcoat</td>
<td>10nm</td>
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<td>CO+Cr+... Magnetic Layer</td>
<td>25nm</td>
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<td>Ni-P Sublayer</td>
<td>10Knm</td>
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<tr>
<td>AL-Mg Substrate</td>
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</table>
Hard Disk Drive

• Spindle Motors

• DC Motors
  • Spindle integrated into the motor
  • 3-phase, 8 pole typical
  • Servo controlled

• Requirements
  • High reliability
    • Operate for many years
    • Hundreds of thousands of start/stop cycles
  • Low vibration / wobble
    • Prevent head slaps
    • Keep tracks aligned through rotation
Hard Disk Drive

• Write Head

• Inductive write head
  • Ring (core) of magnetically soft material
  • Small gap at one end
  • Conductor wrapped around a portion of the ring
Hard Disk Drive

• Write Head

• Inductive write head
Hard Disk Drive

• Write Head

  • Inductive write head – key features

    • Small gap $\rightarrow$ higher linear density (bits per inch)
      $\rightarrow$ smaller side fields $\rightarrow$ higher tracks per inch

    • Narrow head $\rightarrow$ higher number of tracks per inch

    • Material needs high flux density to overwrite the disk material

    • Low electrical inductance for fast bit transitions

    • Mechanically strong – for the occasional head slap

    • Light weight – to make it easy to support at the end of the head arm
Hard Disk Drive

- Write Head

- Thin Film – Inductive write head
Hard Disk Drive

• Read Head

  • Can use the write head for reading

  • Changes in the magnetic field on the disk cause a change in the magnetic flux of the head

  • Changes in magnetic flux cause a voltage to be induced in the coil

  • The voltage is then read by the read circuitry

  • No longer used!
Hard Disk Drive

• Read Head

• Magnetoresistance
  
  • Electrical resistance of a material changes when the material is subjected to an external magnetic field

\[ \Delta R = C_{MR} \cdot R \cdot \cos^2 \theta \]

R = nominal resistance

\( C_{MR} = \text{magnetoresistive coefficient} \sim 2-3 \% \)

\( \theta = \text{angle between the resulting internal magnetic field and the direction of current flow} \)
Hard Disk Drive

- Read Head
  - MR Read Head
    - We are looking for transitions → external field is up or down
    - Bias the easy axis to 0° wrt. the direction of current flow during manufacturing
      - This puts $\Delta R$ at max in the middle of a bit
      - This puts $\Delta R$ at min at the transitions
    - Sense the change in voltage to read whether a transition has happened or not
    - Physically shielded to ensure only one transition is detectable at a time
Hard Disk Drive

- Read Head

\[ \Delta R = C_{MR} \cdot R \cdot \cos^2\theta \]

Min \( \Delta R \) (90° wrt current flow)

Max \( \Delta R \) (No component vertical wrt current flow - 0°)
Hard Disk Drive

• Read Head

• Giant Magnetoresistive Read Head (GMR)
  • Uses semiconductor technology to create stacked layers
  • $\Delta R$ is 5-8% vs 2-3% for MR $\Rightarrow$ more sensitive
Hard Disk Drive

• Read/Write Head

• Combine the best of read and write technology
  • Able to optimize both independently
Hard Disk Drive

• Read/Write Head
  • Read head in front of write head
  • Write wide – read narrow
    • Write head is wider than read – writes a wider track
    • Read head placement does not need to be perfect
    • Builds in a guard band for noise
  • Write width determined by the narrow pole of the write head
  • Track pitch = write width + guard band
    • Guard band protects adjacent tracks from being overwritten
Cross-track profile

cross-track profiles of $H_x$, $H_y$, and $H_\zeta$ at $z=0$

Down-track profile

down-track profiles of $H_x$, $H_y$, and $H_\zeta$ at $z=0$

2D profile

[(Cross-track profile diagram)]

[(Down-track profile diagram)]

[(2D profile diagram)]
Hard Disk Drive

- Write Head
- Inductive write head
Hard Disk Drive

- Inductive Write Head P2 Layer
- Pole Width
- Inductive Write Head P1 Layer & Top Shield
- Write Gap Width
- Copper Write Coils
- Throat Height
- GMR Contacts & Hard Bias
- Bottom Shield
- GMR Read Sensor

SEM x-section image:
- Write Pole
- Write gap
- Trailing Shield
- Reader

Graphs showing the down-track RIR profile and cross-track RIR profile for various FL values.
Hard Disk Drive

• Read/Write Head

• Tracks per inch (tpi)
  \[ Tpi = \frac{1}{\text{track pitch}} = \frac{1}{(W + \text{guard band width})} \]
  \[ W = \text{write width} \]
  \[ \text{Guard band} \ll W \]

• Flux change density
  • Density of transitions
  • \[ \frac{1}{B}, \text{where } B \text{ is the bit length} \]

• Bits per inch (bpi)
  • Assuming no coding – \[ \frac{1}{B} \]

• \( W \) to \( B \) ratio is approximately 4:1
Hard Disk Drive

- Read/Write Head
Hard Disk Drive

• Slider

  • Holds the R/W heads in position over the disk

  • Ride hydrodynamically on a cushion of air – air bearing
    • Tuned to provide an optimum flight height

  • Difficult due to the fact that the air is moving at different speeds at different radii.

  • Rotates to a ramp when drive is not spinning so the head does not contact the ramp.
Hard Disk Drive

• Actuator
  • Electromechanical actuator
    • Rotates the sliders back and forth across the disk
Hard Disk Drive

- Actuator
- Movie