Hard Disk Drives
Electro-Mechanical

Last updated 2/13/24

Hard Disk Drive – Electro-Mechanical

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

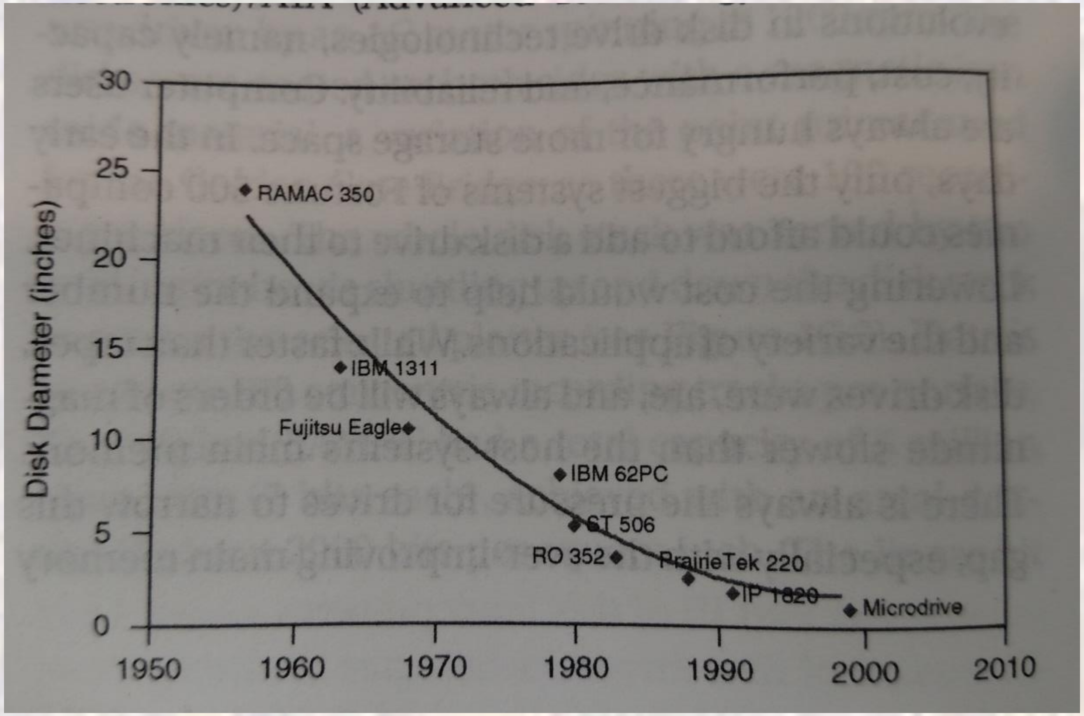
100 bits/in – inside track

55 bits/in – outside track

1s average access time

Hard Disk Drive – Electro-Mechanical

- History
  - Disk Diameter



* Memory Systems, Jacob et. al.

Hard Disk Drive – Electro-Mechanical

- History
  - Areal Density

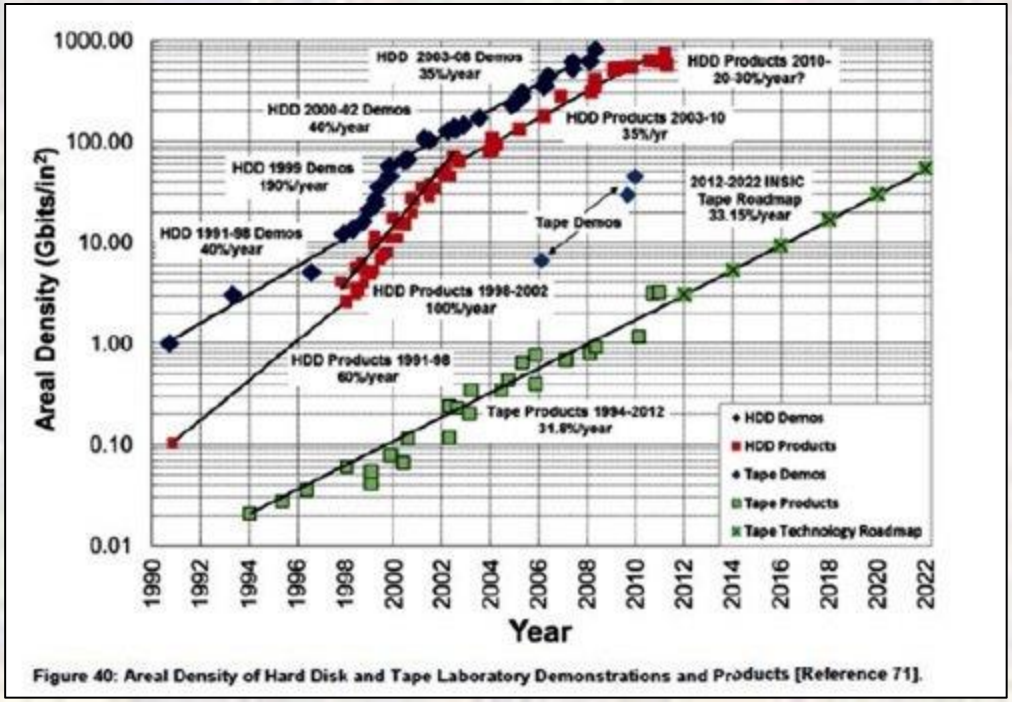
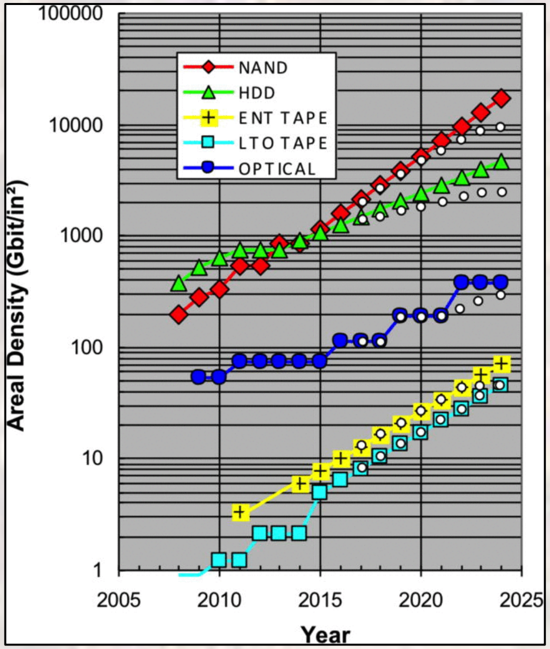


Figure 40: Areal Density of Hard Disk and Tape Laboratory Demonstrations and Products [Reference 71].

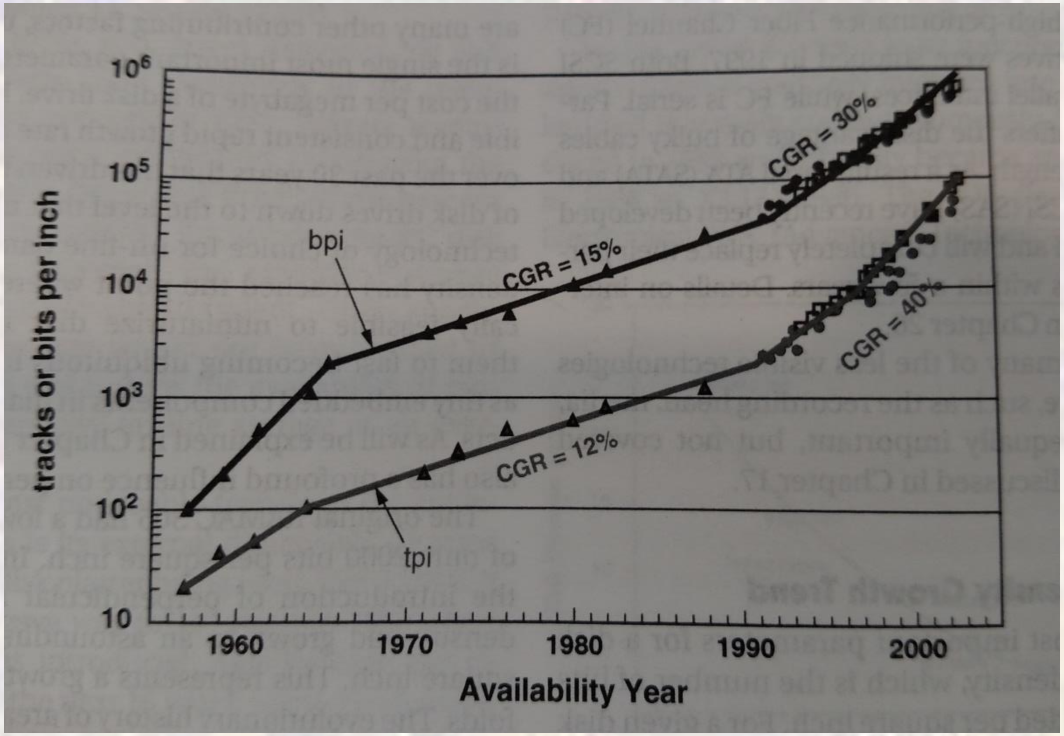
Src: InSIC



Src: JAP 117

Hard Disk Drive – Electro-Mechanical

- History
  - Linear Density



* Memory Systems, Jacob et. al.

Hard Disk Drive – Electro-Mechanical

- History
  - Units

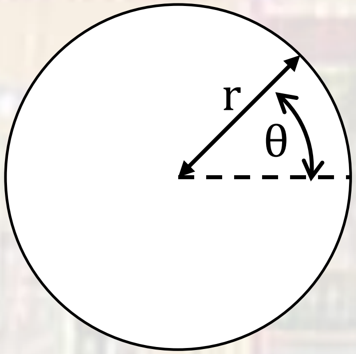
Src: Forbes

Hard Disk Drive – Electro-Mechanical

- 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

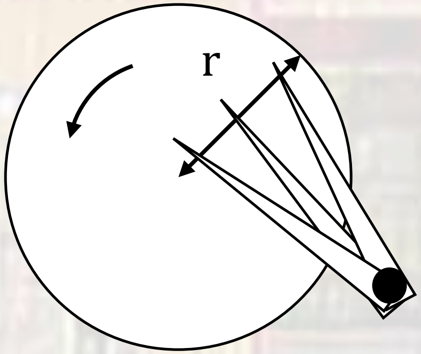
Hard Disk Drive – Electro-Mechanical

- Fundamentals
  - Rotating Storage Devices
    - Information is stored in rings around the disk
      - Concentric
      - Spiral
    - Two values locate all information



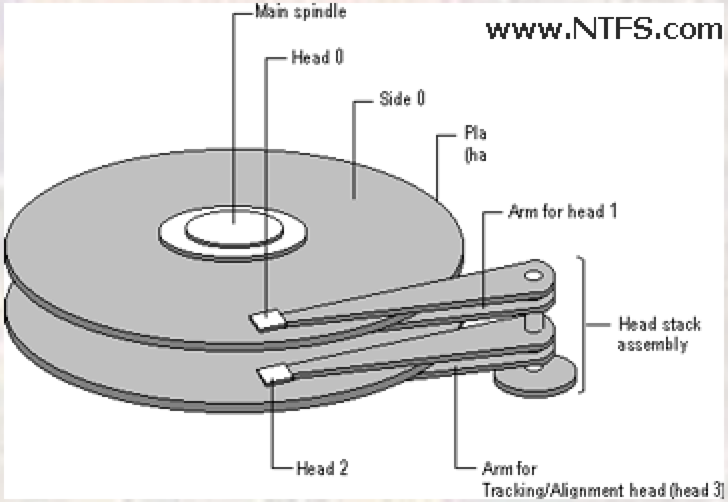
Hard Disk Drive – Electro-Mechanical

- Fundamentals
  - Rotating Storage Devices
    - A movable Arm allows access for variable r
    - Rotating Disk allows access to θ



Hard Disk Drive – Electro-Mechanical

- Fundamentals
  - Rotating Storage Devices
    - Multiple Disks
    - 2 sided
    - Multiple Read/write heads



Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

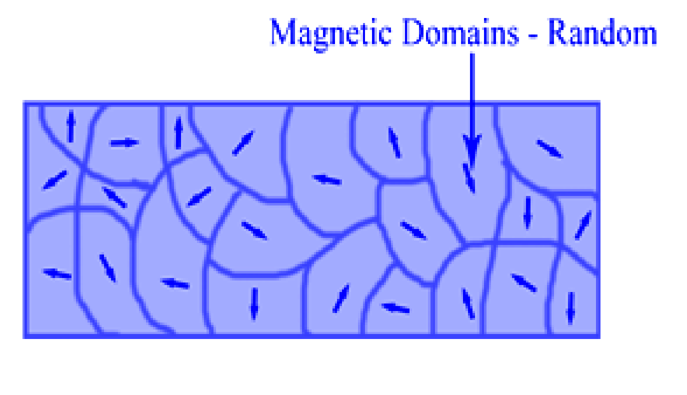
- Fundamentals
  - Disk Drive Performance
    - Response Time - Average
      - Time from command issue to transfer complete
      - Dependent on type of operation
        - R/W, sequential/non-sequential
    - Throughput (Bandwidth)
      - Data transfer rate
      - MB/s
    - Multiple requests
  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

Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

- Physical Layer
  - Magnetic Domains
    - Small regions 1mm^3
    - Materials with unpaired electrons → net magnetic field
    - Micro-structure of the material causes the magnetic fields to align
    - In most materials these domains are random → no net magnetism
    - Ferro-magnetic materials

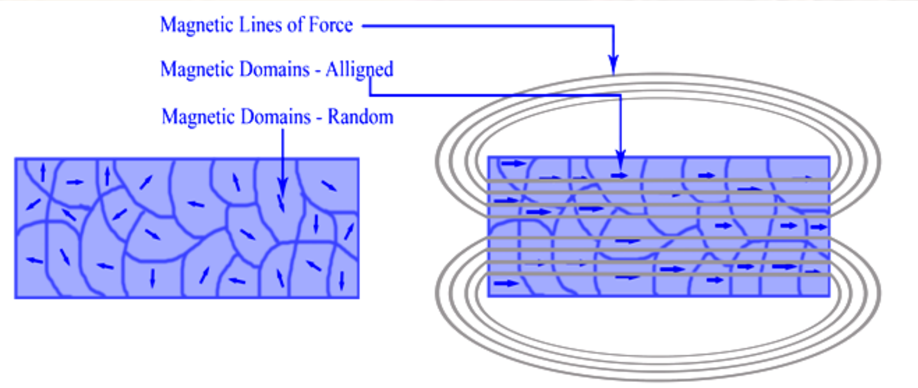


Hard Disk Drive – Electro-Mechanical

- Physical Layer

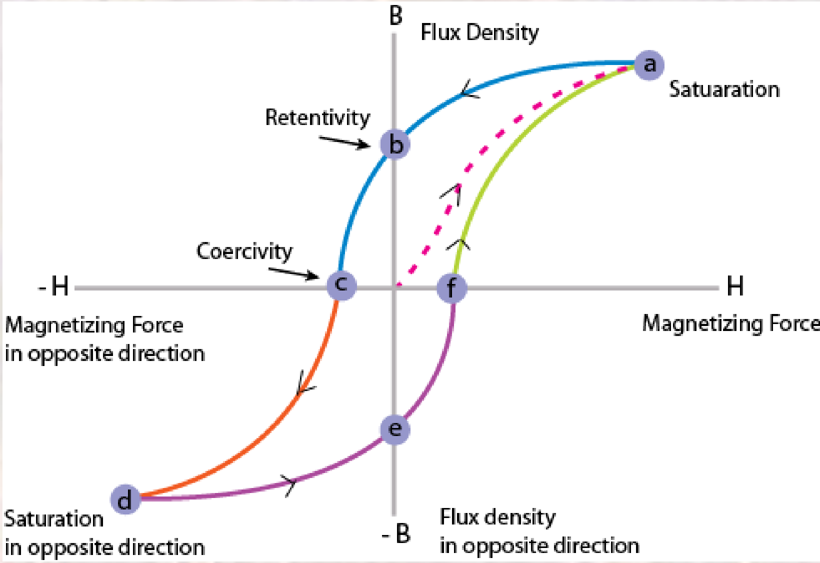
  - Ferromagnetism
    - Materials with magnetic domains
    - When an external magnetic field is applied
      - The magnetic fields of the domains align
    - When the external magnetic field is removed
      - The magnetic fields of the domains remain aligned
      - Leaving behind a material that creates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

    - The material has been magnetized



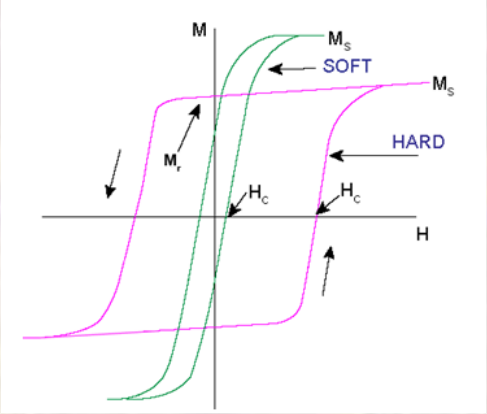
Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

- 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)

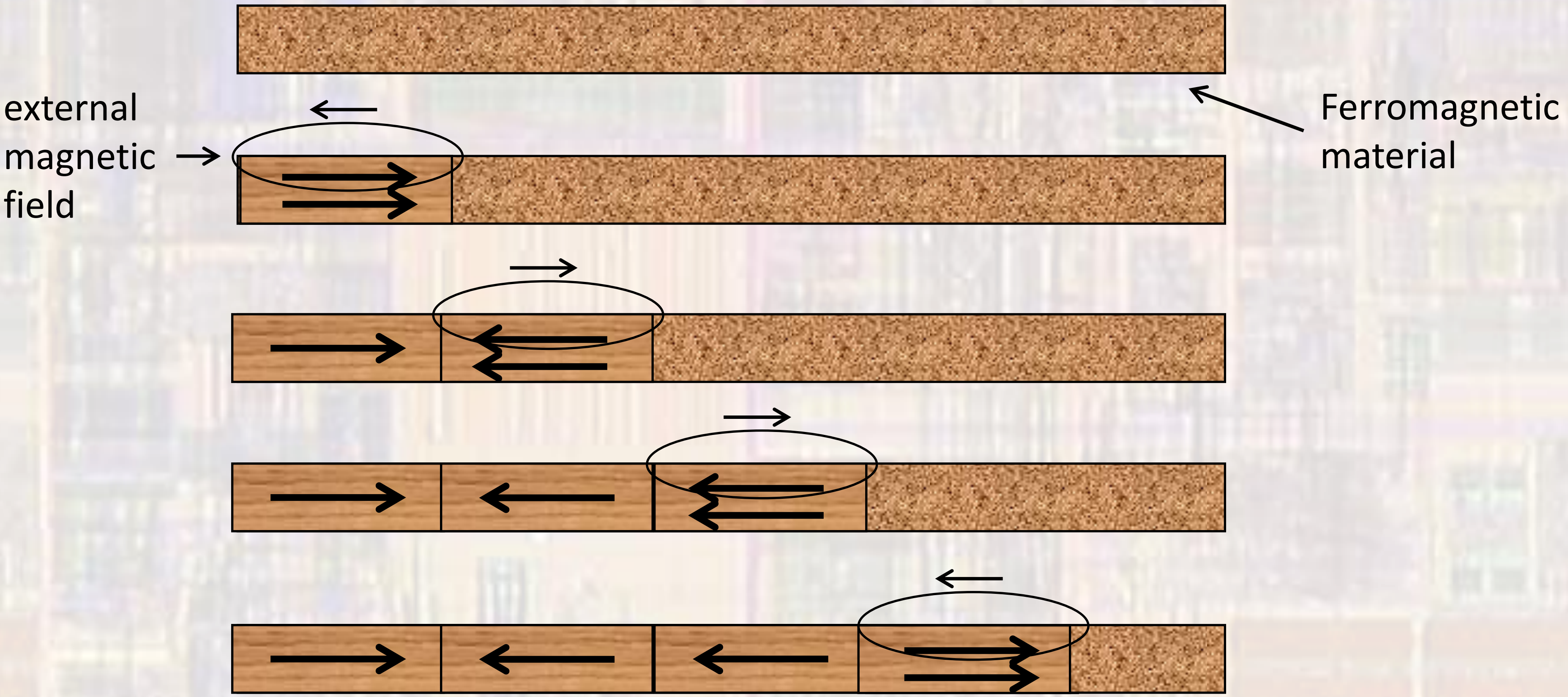


Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

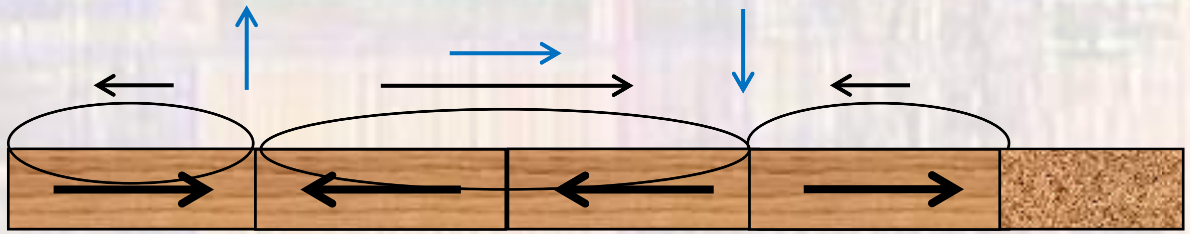
- Writing



Hard Disk Drive – Electro-Mechanical

- Reading

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

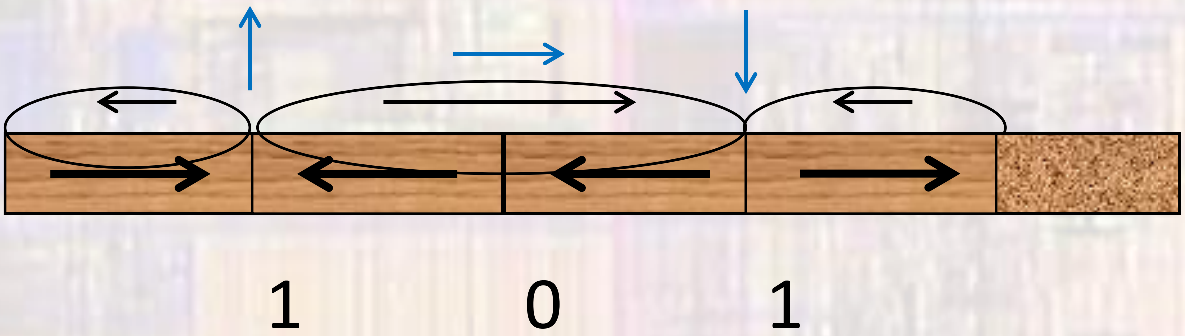


  - Information is NOT stored in the direction of the magnetization

  - Information is stored in the transitions
    - Transition → 1 Independent of direction of change
    - No transition → 0 Independent of the current magnetization direction

Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

- 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 – Electro-Mechanical

- 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 – Electro-Mechanical

- 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 – Electro-Mechanical

- 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

Lubricant	1nm
Carbon Overcoat	10nm
CO+Cr+… Magnetic Layer	25nm
Cr Underlayer	50nm
Ni-P Sublayer	10Knm
AL-Mg Substrate	

Hard Disk Drive – Electro-Mechanical

- Spindle Motors

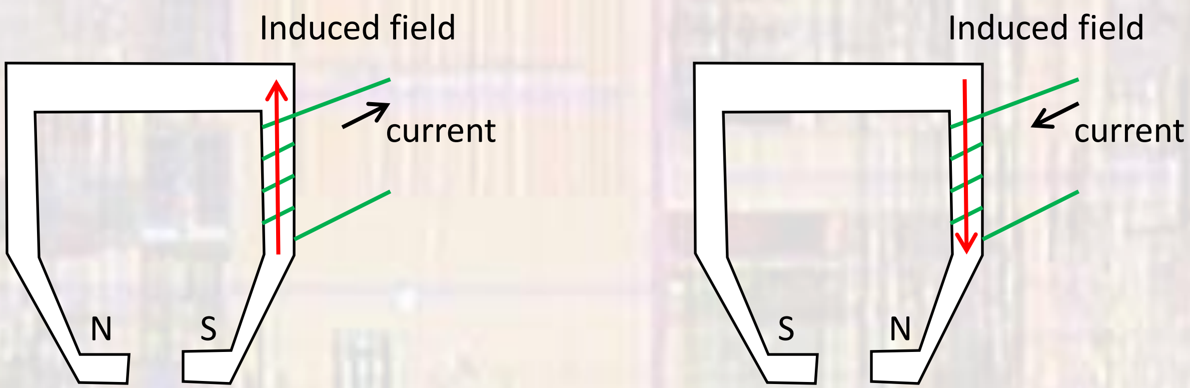
  - DC Motors
    - Spindle integrated into the motor
    - 3-phase, 8 pole typical
    - Servo controlled

  - 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 – Electro-Mechanical

- Write Head

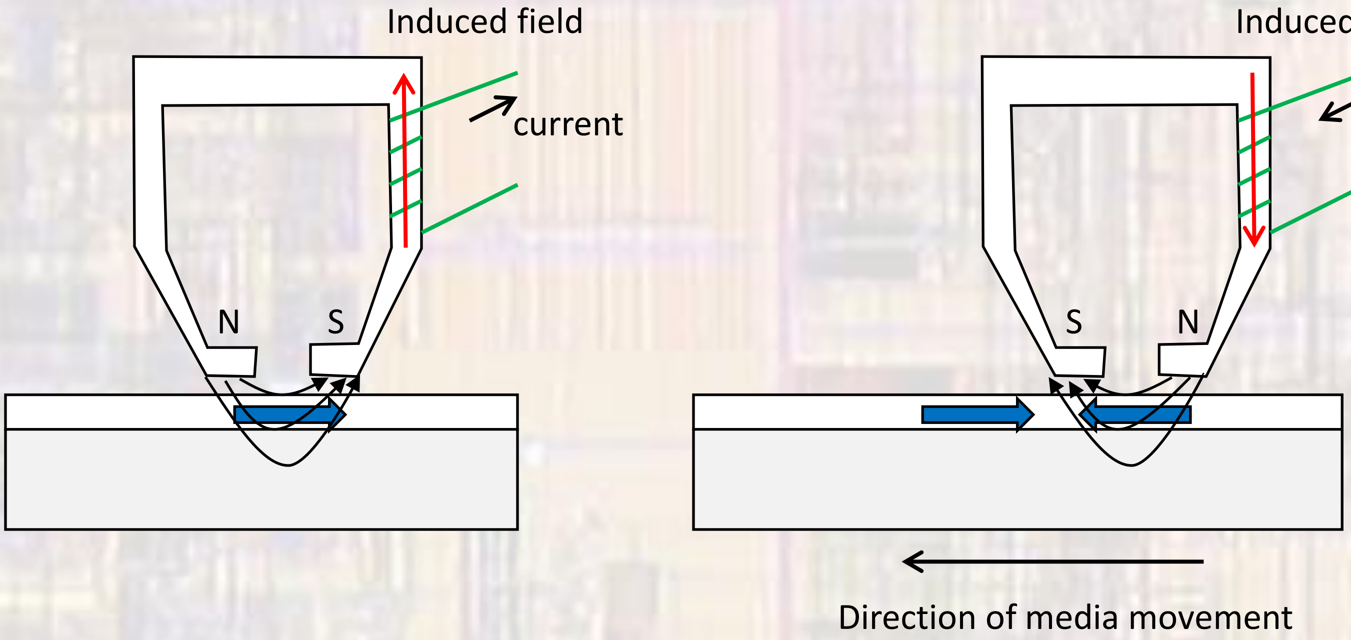
- Inductive write head
  - Ring (core) of magnetically soft material
  - Small gap at one end
  - Conductor wrapped around a portion of the ring



Hard Disk Drive – Electro-Mechanical

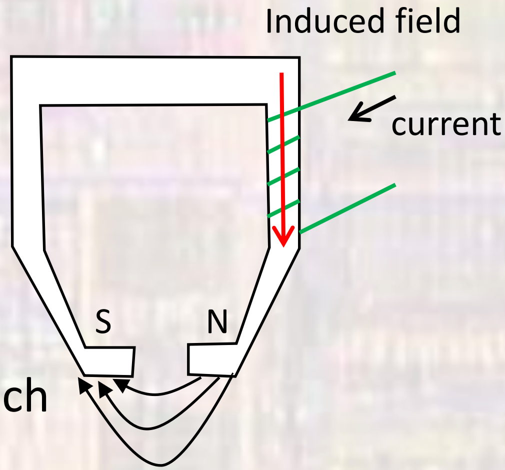
- Write Head

  - Inductive write head



Hard Disk Drive – Electro-Mechanical

- Write Head

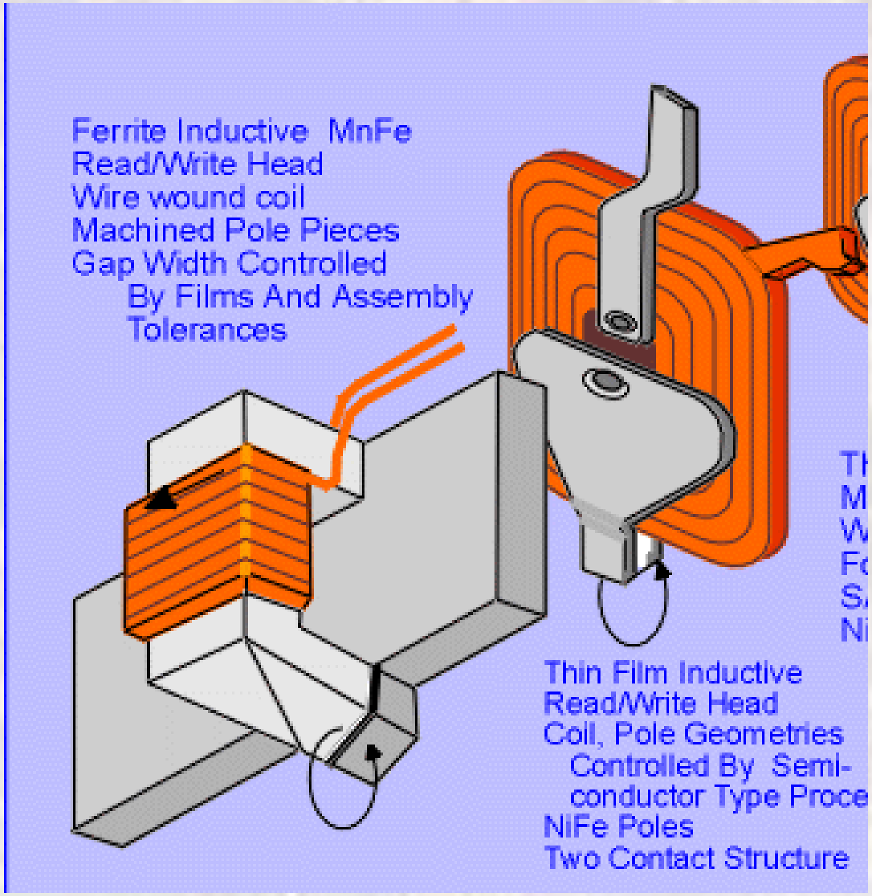


  - Inductive write head – key features
    - Small gap → higher linear density (bits per inch)
      → smaller side fields → higher tracks per inch
    - Narrow head → higher number of tracks per inch
    - Material needs high flux density to overwrite the disk material
    - Low electrical inductance 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 – Electro-Mechanical

- Write Head

  - Thin Film – Inductive write head



Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

- Read Head
  - Magnetoresistance
    - Electrical resistance of a material changes when the material is subjected to an external magnetic filed

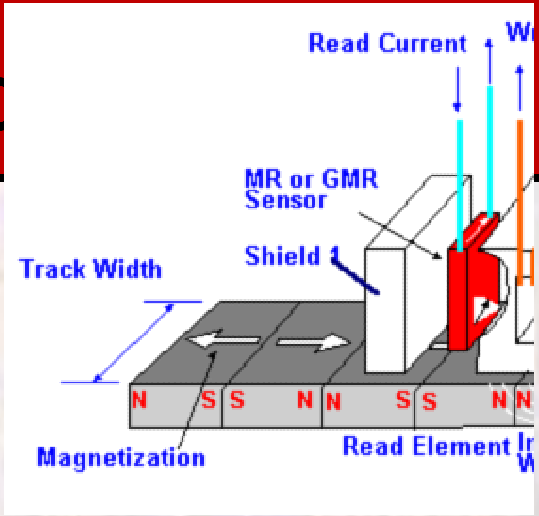
$$\Delta R = C_{MR} \cdot R \cdot \cos^2\theta$$

R = nominal resistance

C_{MR} = magnetoresistive coefficient ~ 2-3 %

θ = angle between the resulting internal magnetic field and the direction of current flow

Hard Disk Drive – Electro



- Read Head

  - MR Read Head

    - We are looking for transitions → external field is up or down

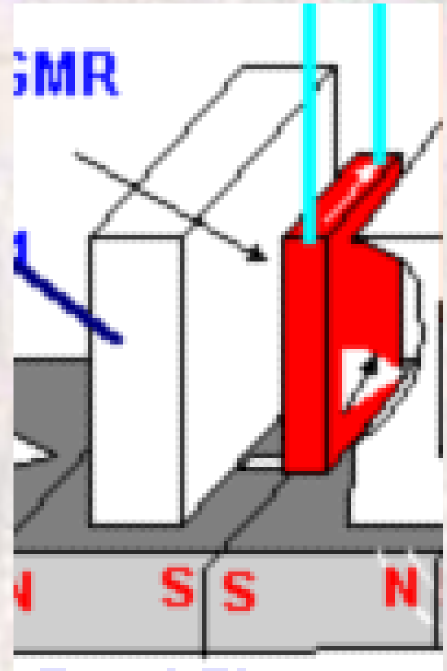
    - Bias the easy axis to 0° wrt. the direction of current flow during manufacturing
      - This puts ΔR at max in the middle of a bit
      - This puts ΔR at min at the transitions

    - 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

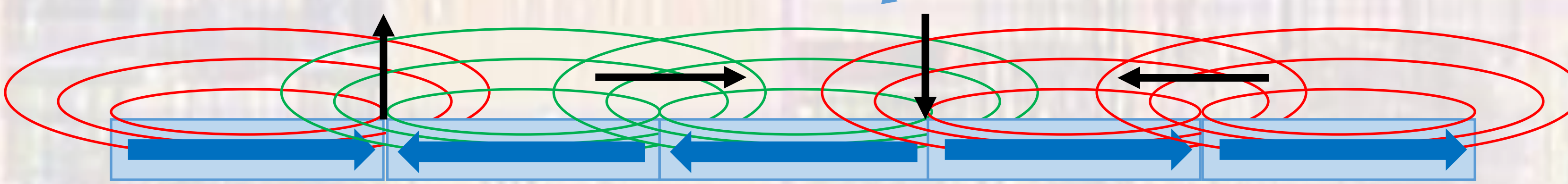
Hard Disk Drive – Electro-Mechanical

- Read Head



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

Min ΔR (some component wrt current flow)



Max ΔR (No component wrt current flow)

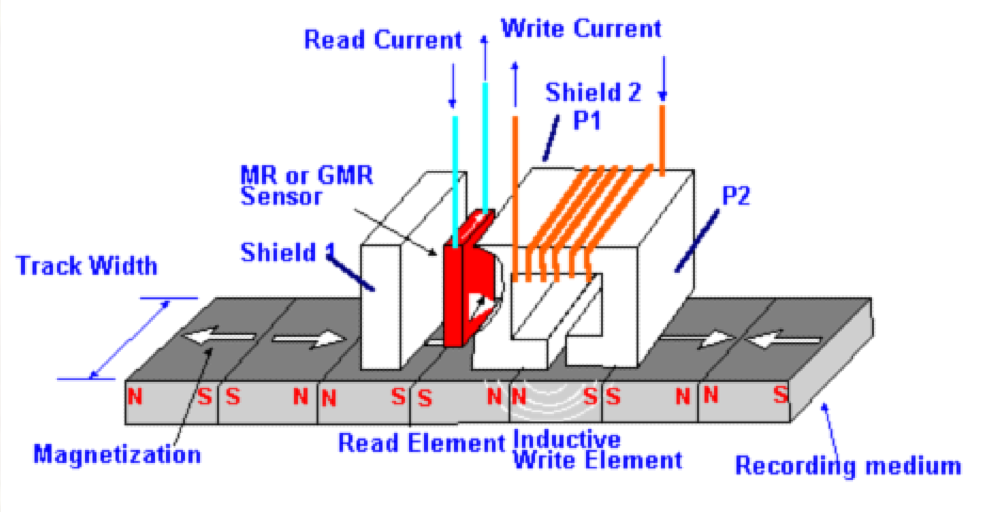
Hard Disk Drive – Electro-Mechanical

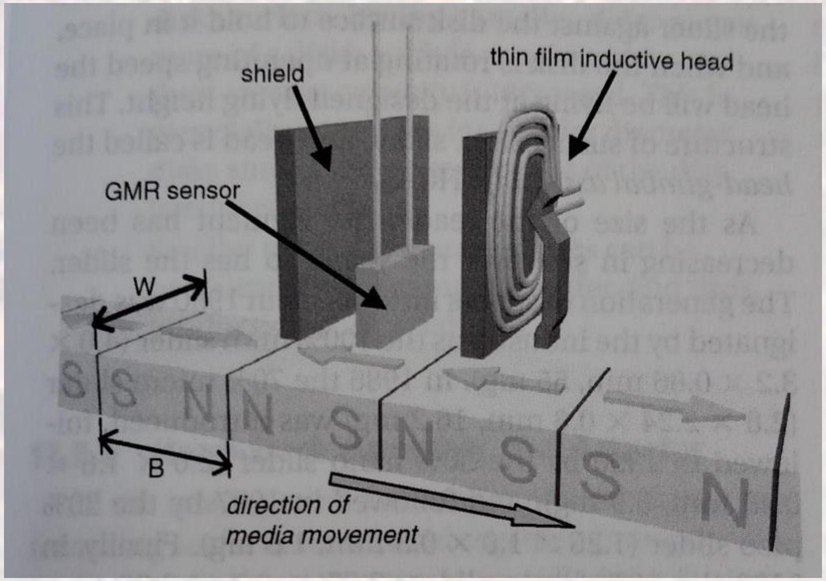
- Read Head
  - Giant Magnetoresistive Read Head (GMR)
    - Uses semiconductor technology to create stacked layers
    - ΔR is 5-8% vs 2-3% for MR → more sensitive

Hard Disk Drive – Electro-Mechanical

- Read/Write Head

- Combine the best of read and write technology
  - Able to optimize both independently



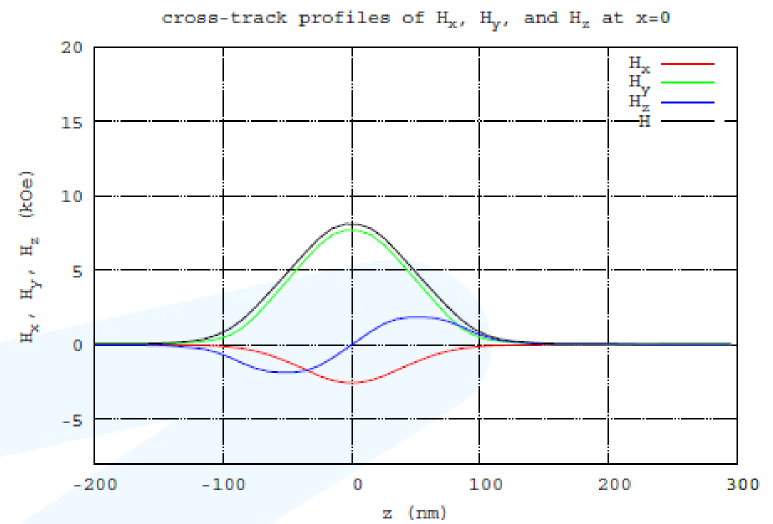


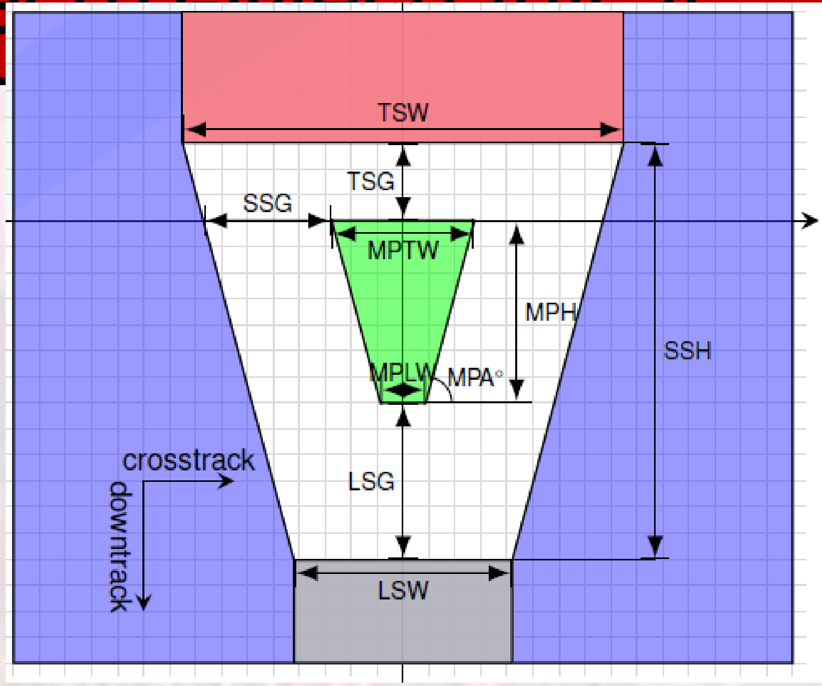
Hard Disk Drive – Electro-Mechanical

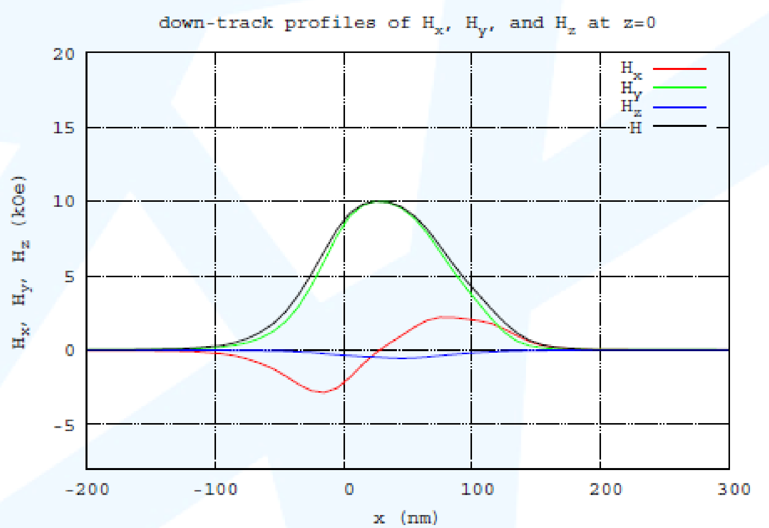
- Read/Write Head
  - Read head in front of write head
  - Write wide – read narrow
    - Write head is wider than read – writes a wider track
    - Read head placement does not need to be perfect
    - Builds in a guard band for noise
  - Write width determined by the narrow pole of the write head
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

Electro-Mechanical

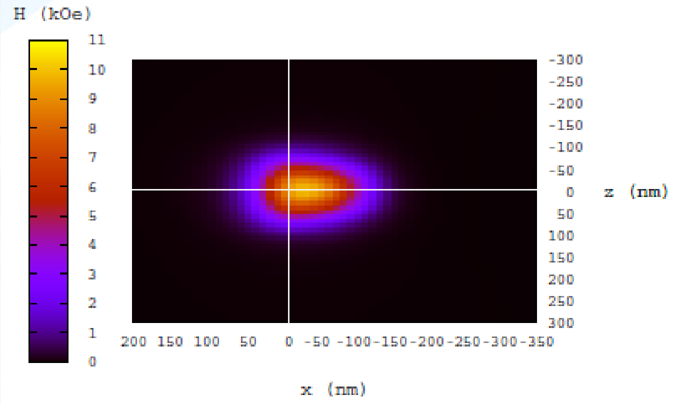
Cross-track profile







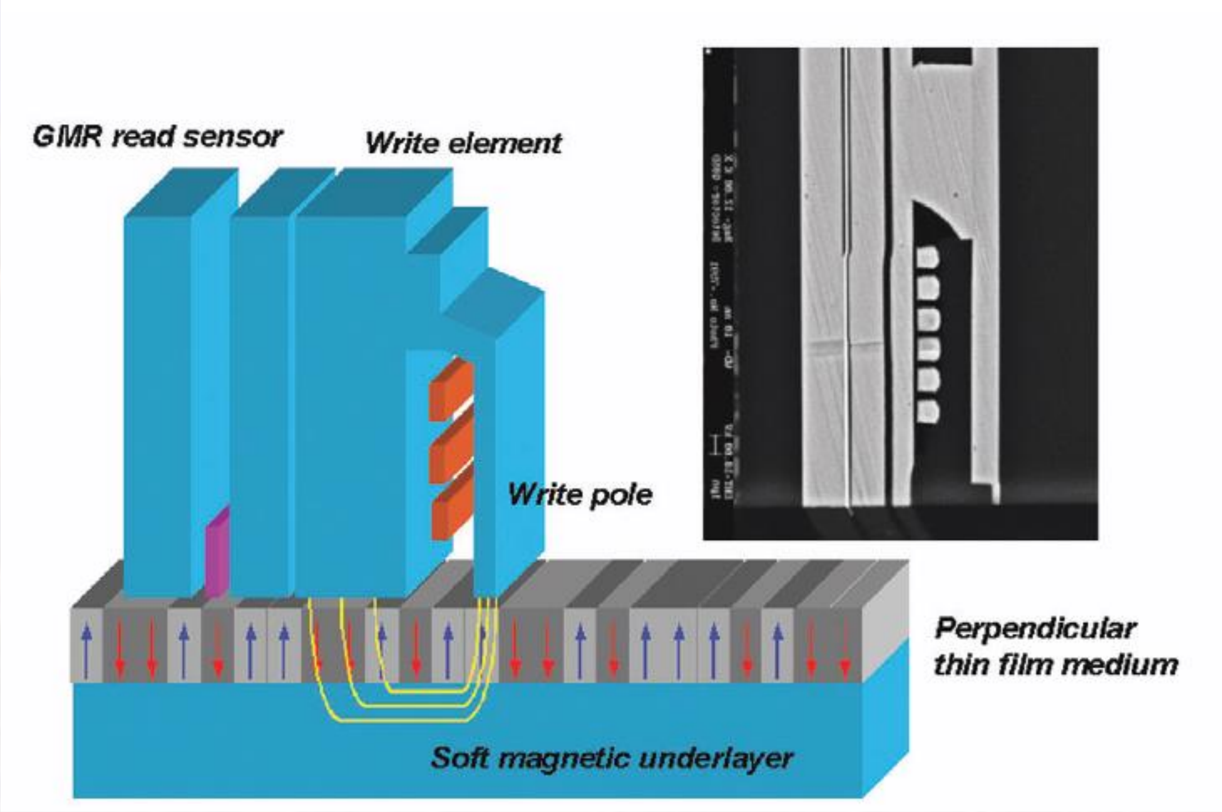
Down-track profile



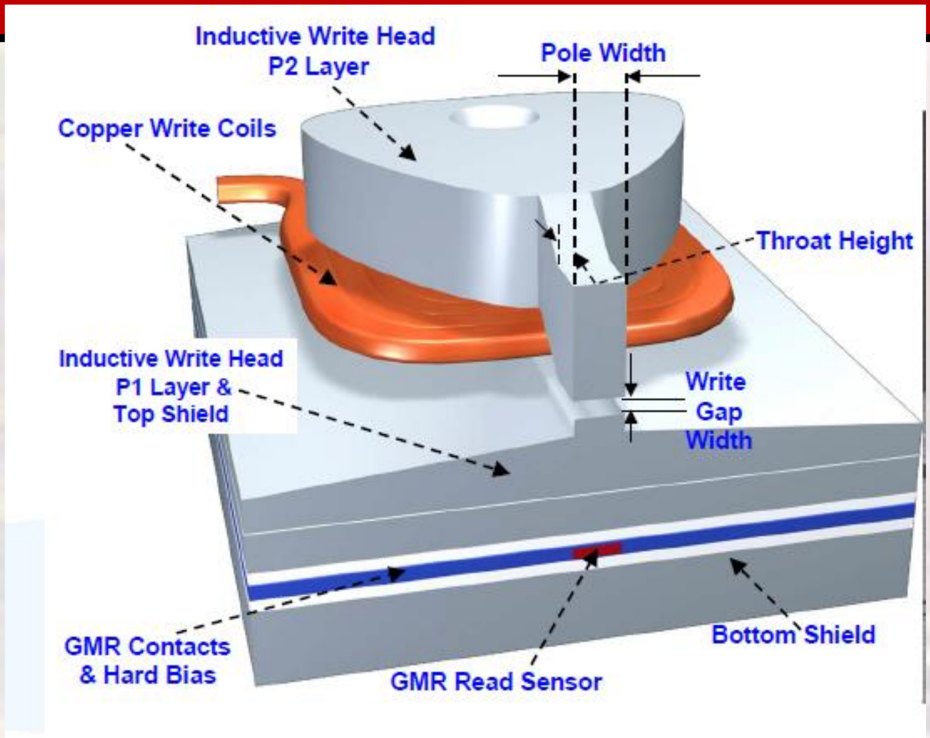
2D profile

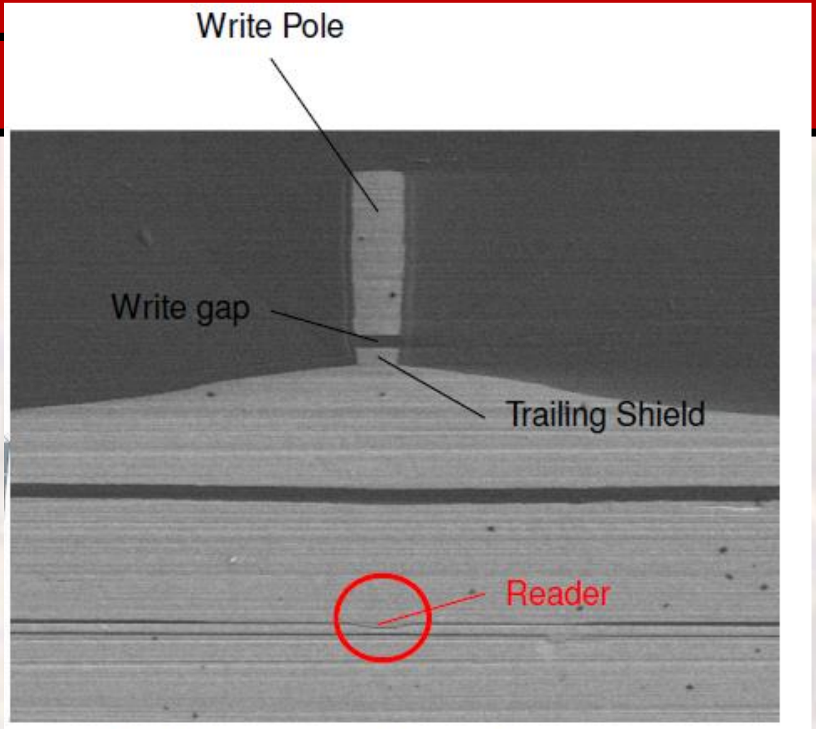
Hard Disk Drive – Electro-Mechanical

- Write Head
  - Vertical recording

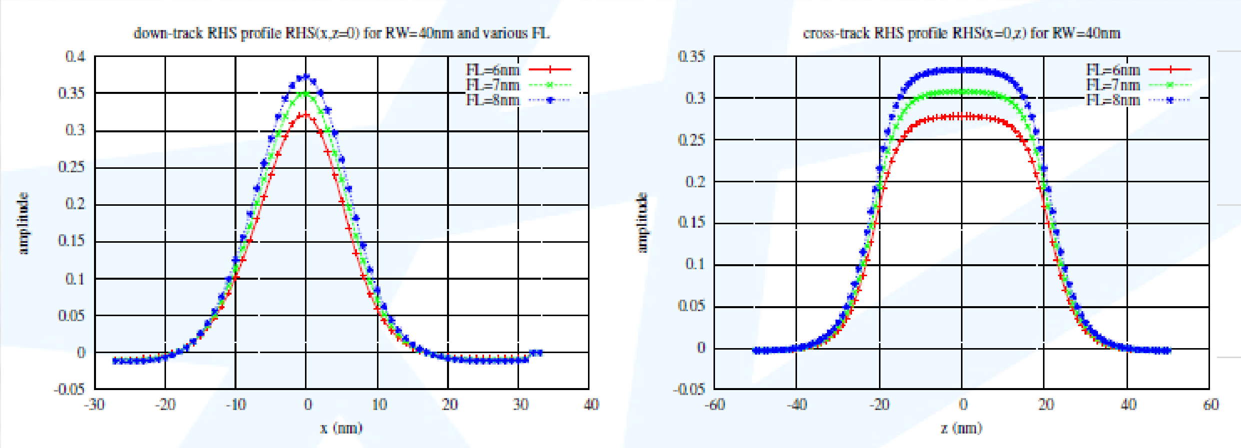


Hard Disk Drive – Elec





SEM x-section image



Hard Disk Drive – Electro-Mechanical

- Read/Write Head

  - Tracks per inch (tpi)

    Tpi = 1/track pitch = 1/(W + guard band width)

    W = write width

    Guard band << W

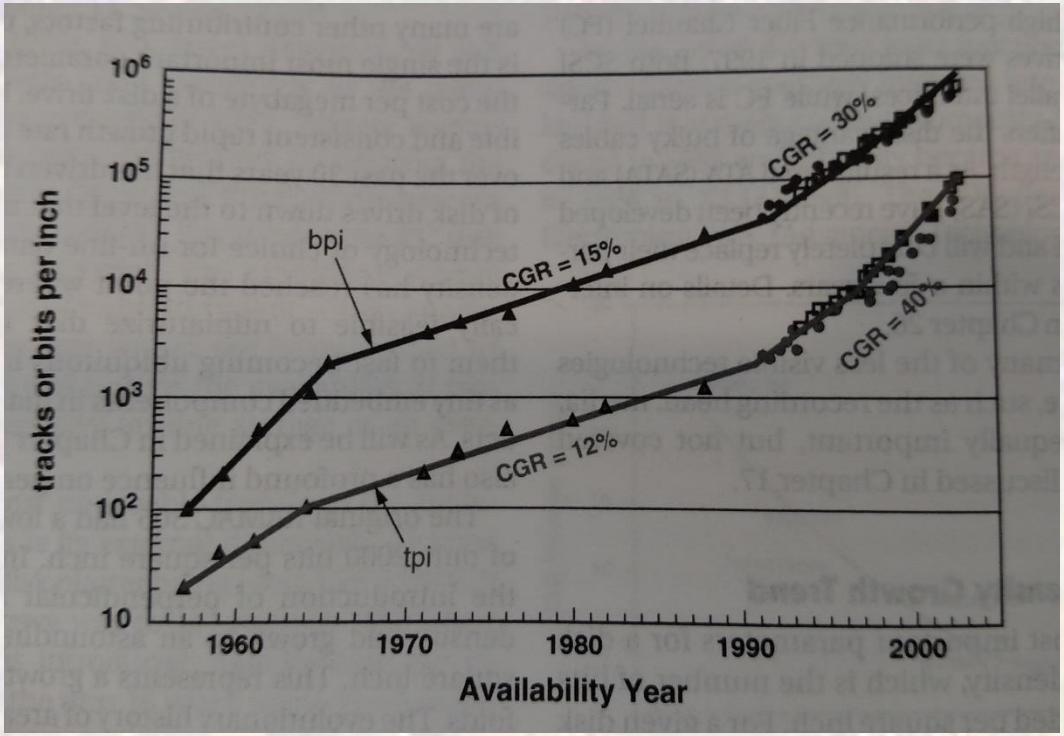
  - Flux change density
    - Density of transitions
    - 1/B, where B is the bit length

  - Bits per inch (bpi)
    - Assuming no coding – 1/B

  - W to B ratio is approximately 4:1

Hard Disk Drive – Electro-Mechanical

- Read/Write Head



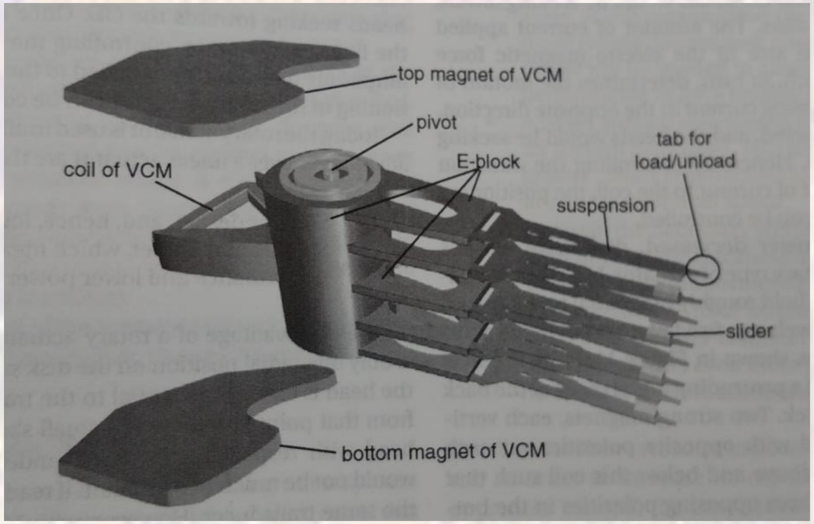
Hard Disk Drive – Electro-Mechanical

- 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 – Electro-Mechanical

- Actuator

  - Electromechanical actuator
    - Rotates the sliders back and forth across the disk



Hard Disk Drive – Electro-Mechanical

- Actuator

  - Movie