UNIVERSITY OF CAMBRIDGE
Department of Engineering

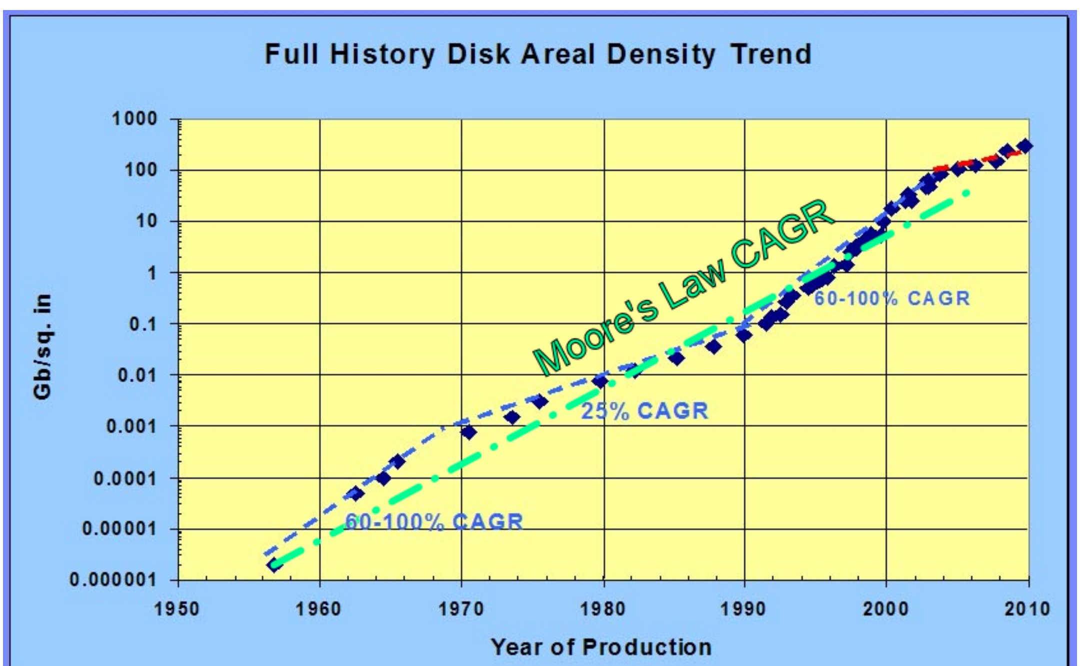
IB Paper 8
Electrical Engineering

Lecture 13
Magnetic Storage

https://www.vle.cam.ac.uk/course/view.php?id=69961

Introduction

- The ability to store data using magnetic materials is a concept that stretches back over 100 years
  - An early example of this was the audio tape
- Despite advances in other data storage technologies (e.g. solid state drives, optical storage) the magnetic hard disk drive (HDD) remains the bedrock of mass data storage
  - Data centres rely on HDDs
  - Since the first commercial HDD was produced by IBM in 1957, the data storage density of HDD technology has followed a Moore's Law-like progression
  - It is the very high data densities and good reliability that HDDs offer which continues to make them attractive



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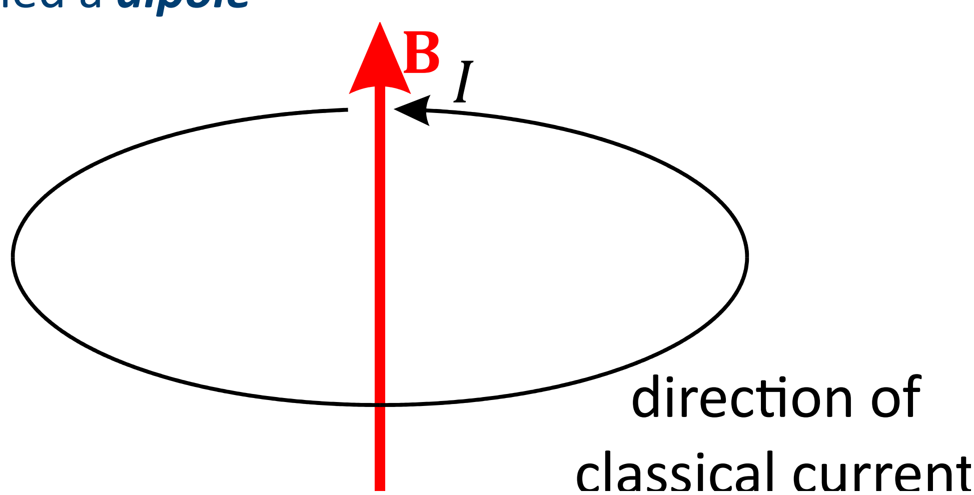
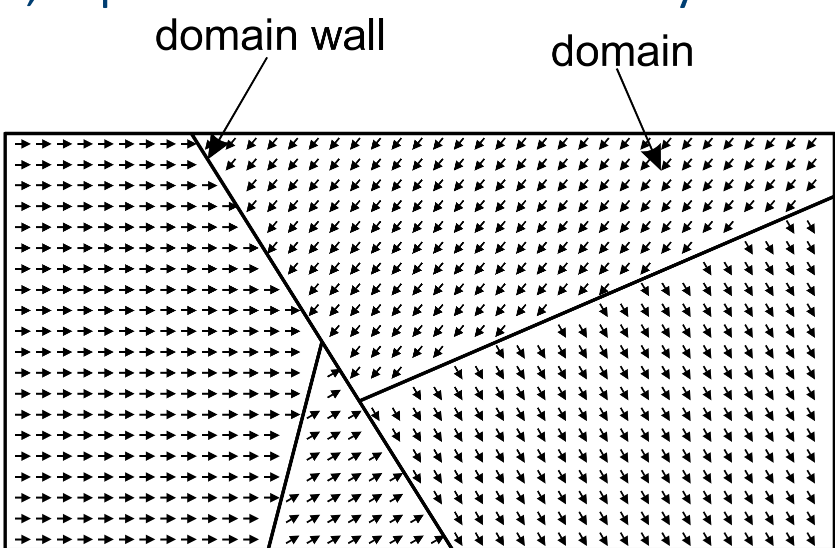
Storing Data using Ferromagnetic Materials

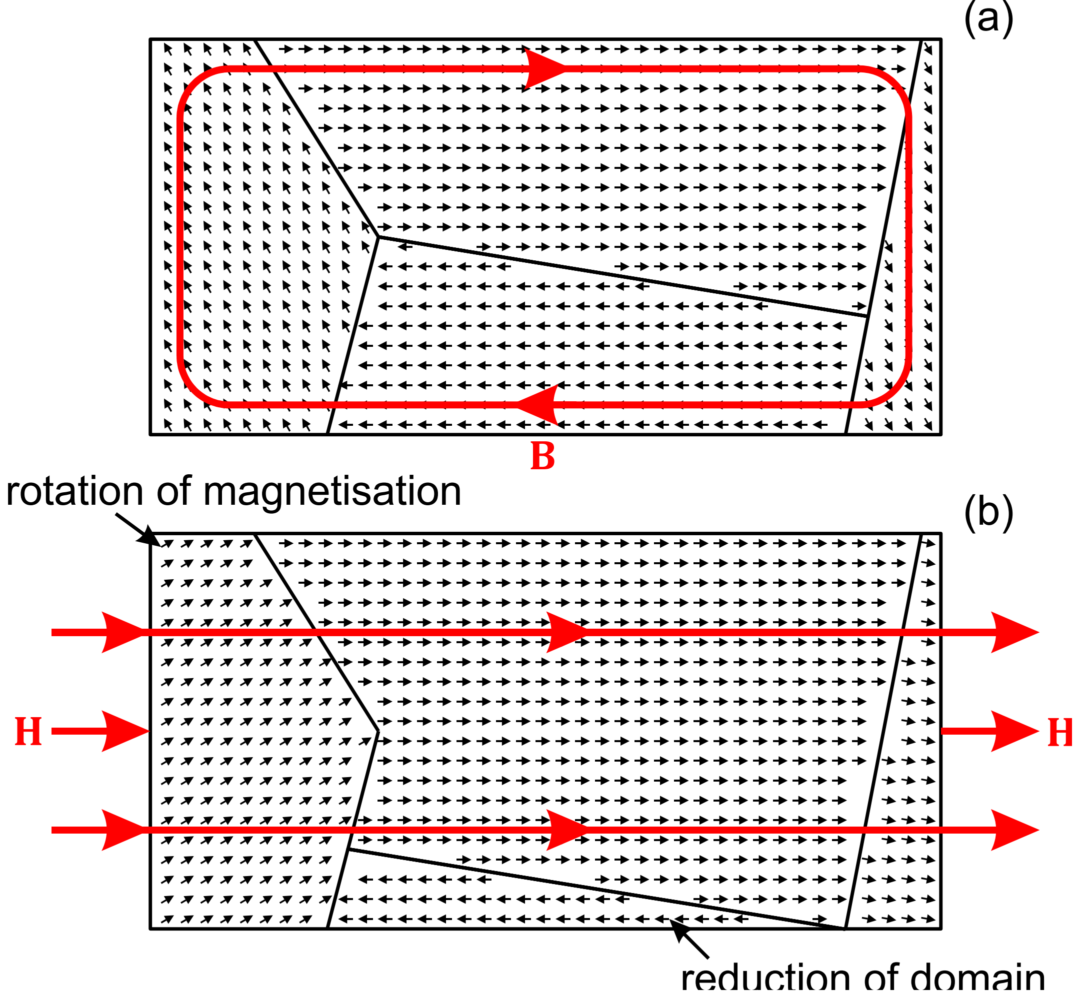
- Storage of binary digital data requires that we have a system which
  1. can exist stably in one of two states
  2. can be switched between the two states
  3. has a measurable difference between the two states
- One suitable system for achieving this is to use ***ferromagnetic materials***
- The origin of ferromagnetism lies at the atomic scale
  - In some elements, and particularly those with unpaired electrons, there can be a net rotation of electronic charge around the nucleus of each atom
  - From the ***Ampère-Maxwell Law***, we know that moving charge produces a magnetic field
  - Therefore each atom has a small magnetic field associated with it, called a ***dipole***



- In many paramagnetic materials, neighbouring atomic dipoles are sufficiently well-separated, and the interaction so weak, that at room temperature there is enough thermal energy to randomly align individual dipoles in a solid, and so macroscopic effect is seen
- In ferromagnetic materials, however, there is a strong quantum mechanical interaction between dipoles
- An example is in materials with spatially extensive 3d electrons
- It becomes energetically favourable for neighbouring dipoles to align parallel to each other creating a local magnetic field (***magnetisation***)
- The energy gain associated with this alignment is not isotropic, but is greatest in certain crystallographic directions, called ***easy directions***
  - In iron the [100] direction is an easy direction
- The result is regions of ferromagnetic material where all of the dipoles are aligned in the same easy direction, called ***domains***, separated from each other by ***domain walls***



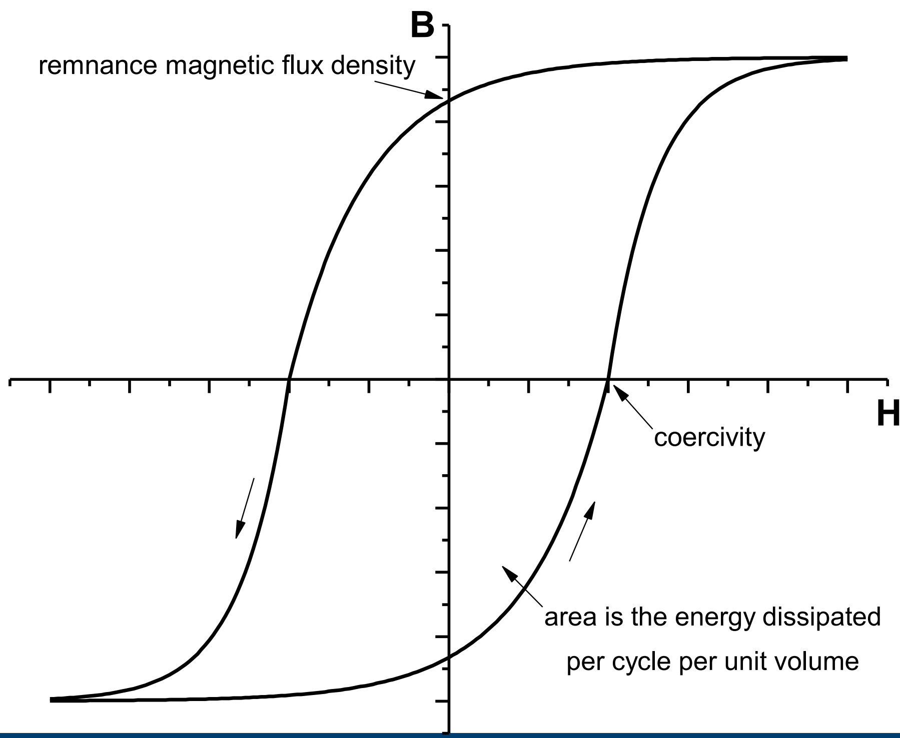
- We could imaging using these domains as a means of storing data
  - We could flip the direction of magnetisation within a single domain in either direction along a specific crystallographic plane to store either a ‘0’ or a ‘1’
- Clearly, we need to make the domains small, but stable, and this implies narrow domain walls, but what determines their width?
  - Across a domain walls, there will be a transition of dipoles pointing in one direction to another
  - A wide wall means that there is a small angular difference between neighbouring dipoles, implying a reduced energy
    - This energetically favours wide walls
  - However, in the wall, the dipoles will not be pointing in an easy direction
    - This energetically favours narrow walls
  - The balance between these two determines actual wall width
  - **For high density data storage, we therefore need materials where there is a high energy penalty for a dipole not pointing in an easy direction**



- In the absence of an external magnetic field, the domains often align to contain the magnetic field within the material, as in (a)
  - Application of an external field will try to cause the dipoles to align with the applied field either by
    1. Rotating dipoles within a domain
    2. Moving domain walls
  - This is shown in (b)
  - **We want process ‘1’ for data storage, so we need the energy to move a domain wall to be high compared with the energy to rotate the dipoles within a domain**

- The magnetisation of ferromagnetic materials is highly non-linear
  - Once all of the dipoles have been aligned with an applied magnetic field (**H**), it is no longer possible to increase the magnetic flux density (**B**), which saturates
  - If the applied magnetic field is removed, then the interaction between neighbouring dipoles will cause a magnetic flux density to remain - the ***remnance flux***
  - A reverse magnetic field has to be applied to remove the magnetic flux – the ***coercivity***
  - It costs energy to go round the B-H hysteresis loop, which is given by the area inside the loop per unit volume
  - The energy stored in magnetising a volume v is

$$U = \int_v \int_0^{\mathbf{H}} \mathbf{B}.\, d\mathbf{H}\, dv \qquad (13.1)$$



- We want ***hard magnetic materials*** with a high remnance
- We also need the domain associated with each bit of data to be stable in a given state, once 'set'
- This implies that there must be an energy barrier between the two states and a high coercivity
- This energy barrier must be proportional to the volume of the domain
  - We define a ***magnetic anisotropy energy density***, *K*, which is this energy barrier per unit volume (typically ~10^4 J m^{-3})
- In the absence of an applied magnetic field, a given domain will switch states randomly with a characteristic average time between switches called ***the Néel Relaxation Time***

$$\tau_N = \tau_0 \exp\left(\frac{Kv}{kT}\right) \tag{13.1}$$

- The constant τ_0 is the time between the domain trying to switch states, is typically ~1 ns (called the ***attempt time***)
- Therefore, if we want τ_N to be at least 10 years

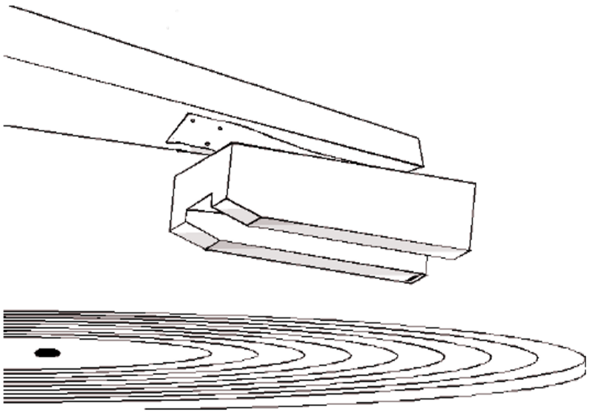
$$\frac{Kv}{kT} = \ln\left(\frac{\tau_N}{\tau_0}\right) = \ln\left(\frac{3.16\times10^8}{10^{-9}}\right) = 40.3$$

$$Kv = 40.3kT = 1.67\times10^{-19}\text{ J}$$

- This implies a minimum volume of 1.65×10^{-23} m^3
- Assuming a cubic domain, this implies a minimum side length of 25 nm
- This is called the ***superparamagnetic limit***

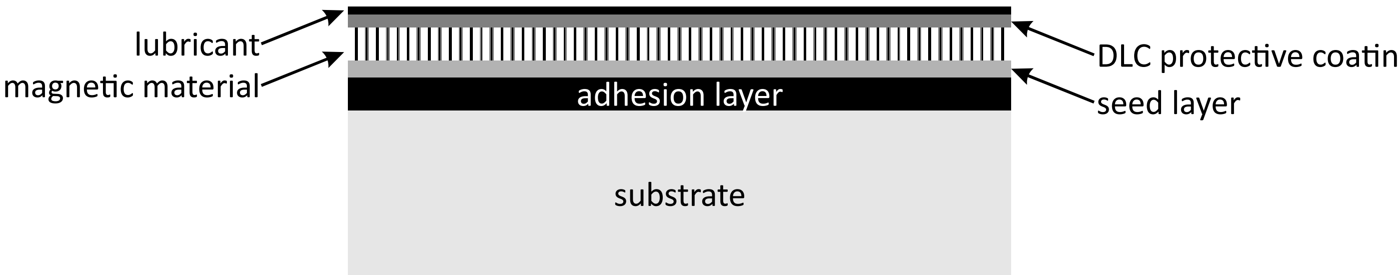
HDD: Key Components

- The key components in the HDD are the disk (often called the ***platter***) and the ***slider***
  - The platter is actually a stack of disks which are made to rotate a very high speeds (~7,000 rpm)
  - A slider then moves a read/write head quickly to any point on the disk
    - This allows random access to data (the original name for these was RAMACs – Random Access Method of Accounting and Control)
  - The slider is actuated magnetically using a magnetic voice coil as this does not require mechanical contact to the slider and is temperature independent
  - The slider then 'flies' over the surface of the disk at very high speed (effectively getting well over 50 mph)
    - The head slider has been aerodynamically designed so that that it is supported by an air cushion
    - This allows the distance between the disk and the head to be ~10 nm



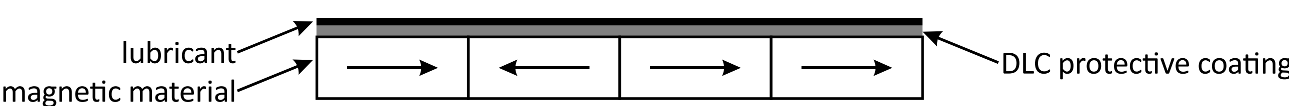
The Disk

- The disk consists of a number of elements

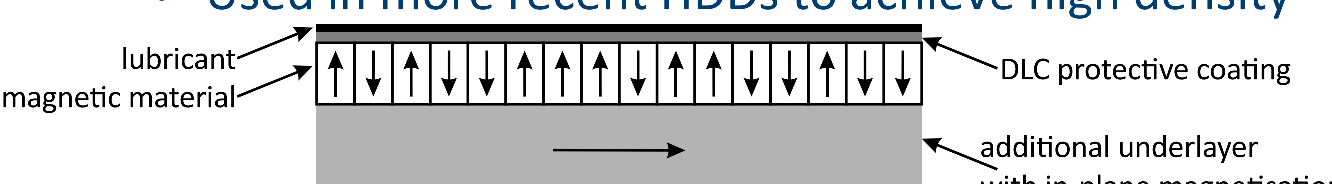


- Substrate
  - This is the main mechanical body of the disk
  - It is commonly made from either aluminium or glass and both sides are usually used for data storage
  - Subsequent layers are then deposited onto the substrate, usually by sputtering (see Lecture 10, Slide 8)
- Underlayer
  - A layer is coated onto the substrate to improve adhesion of the subsequent stack of materials, and nickel phosphide is commonly used for this
- Seed layer
  - The microstructure of the magnetic layer in which data is to be stored is clearly critical
  - A very thin film of material which can seed the subsequent growth of the magnetic material so that it has the right grain size and grain orientation is therefore used
  - This only needs to be very thin (< 10 nm) and chromium is often used

- Magnetic material
  - The magnetic material itself is usually a thin (~50 nm) film of a cobalt alloy, such as CoCr
  - Thin films tend to produce hysteresis curves which are almost square (tending to ideal)
  - The films themselves are polycrystalline in microstructure, but with a well-defined crystal orientation relative to the substrate as a result of the seed layer meaning that the easy directions are also well-defined
  - The grain size is normally much smaller than the size of each domain used to encode bits of data
  - This avoids trying to form domain walls within a single grain, which would otherwise increase the likelihood of the domain wall moving (see Slide 6)
  - There are two basic data recording schemes
    1. Longitudinal recording
       - The magnetisation is in the plane of the substrate
       - Easier to achieve and what most HDDs used up to the mid-2000s, but limits data density



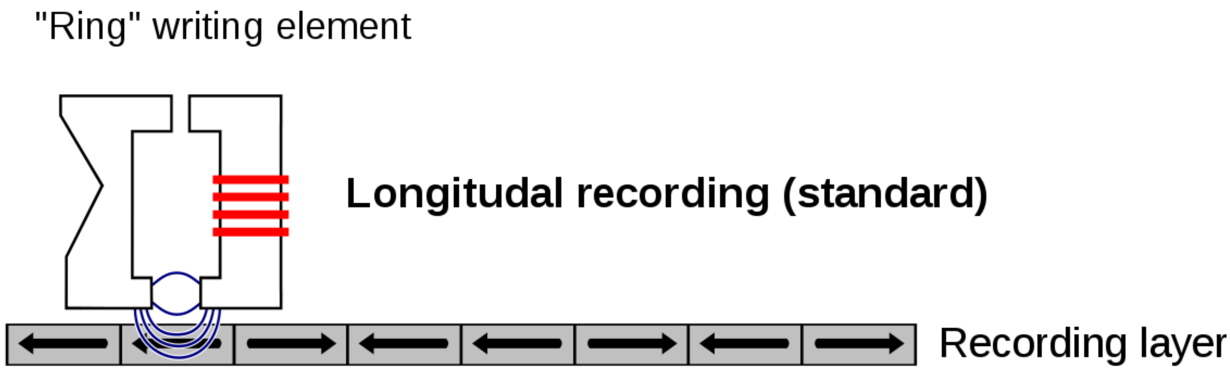
    2. Perpendicular recording
       - Used in more recent HDDs to achieve high density



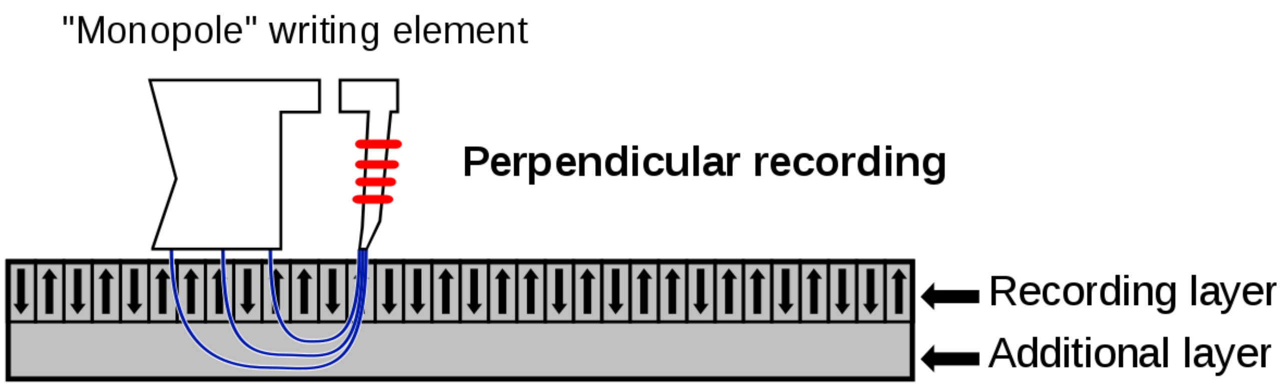
- Protective Coating
  - A hard, but thin protective coating is applied over the magnetic material to give mechanical protection
  - The closer the head can get to the magnetic material, the smaller the physical size of domain that it will be able to read
  - Therefore the protective layer must be very thin and it must be very smooth
  - One option is to use a dielectric like zirconia
  - Diamond-like carbon (DLC) has become popular
  - This is an amorphous form of carbon, but one where most of the carbon atoms have a diamond-like sp^3 bonding rather than a graphitic-like sp^2 bonding
  - The result is a material which retains many of the mechanical properties of diamond, but which can be made in thin films that are exceptionally smooth (sub-nm scale roughness)
- Lubricant
  - Finally, there is a lubricant layer, such as a monolayer of long chain fluorocarbons

Recording Data

- In order to store data, we need to be able to define the magnetisation of each domain in the magnetic material
- This is achieved using inductive coupling, but the precise mechanism depends on whether ***longitudinal*** or ***perpendicular*** recording is being used
  - For longitudinal recording a simple ring writing head is used
    - This consists of a ring of soft magnetic material with an air gap and a current-carrying coil of wire wrapped around the magnetic material
    - Application of a current to the coil will produce a magnetic field around the ring of magnetic material whose direction will depend on the direction of the current
    - The air gap is made sufficiently wide so that there is significant fringing of the magnetic field into the hard magnetic recording layer
    - As long as the coercivity is overcome, then the direction of the magnetic field in the writing head will be permanently stored in the magnetisation of the domain in the magnetic recording layer



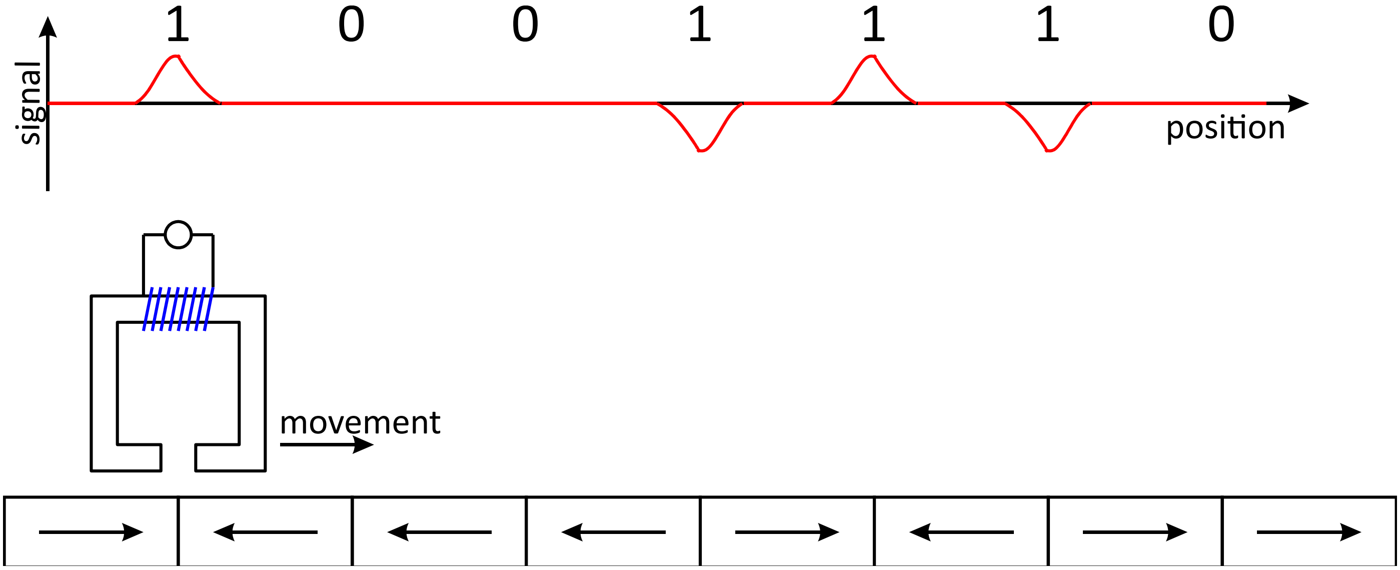
Public domain image



- For perpendicular recording, a similar inductive coupling from a soft magnetic ring and coil is used
  - However, to produce a vertical field, the additional layer under the recording layer becomes important
  - This is easily magnetised longitudinally allowing a magnetic circuit to run from what appears to be a monopole side of the ring with a high field intensity to overcome the coercivity of the recording medium
  - The field runs along the additional layer and back up to the other side of the ring, but this side of the ring has a much bigger area so the magnetic field is reduced below the coercivity of the recording medium

Reading Data

- There are two methods of reading data from the disk: ***inductively*** or by ***magnetoresistance***
- Inductive reading was widely employed for many years, and is sometimes still used
  - The read head consists of a ring of soft magnetic material with a coil wrapped around part of it, in a very similar construction to the reading head
  - This time, however, the fringing field from the magnetic domain couples into the read head to create a magnetic circuit
  - If there is a difference in the direction of magnetisation between two neighbouring domains, then the change in magnetic field passing round the magnetic circuit as the head moves from one domain to the other will induce a current in the coil (Faraday's Law) – this represents a '1'
  - If there is no difference in the direction of magnetisation between neighbouring domains, then there is no current induced, and this represents a '0'
    - Therefore, it is not the absolute direction of magnetisation of an individual domain that encodes the data – it is the difference or similarity between the magnetisation direction of neighbouring domains that is important



- The second means of reading the data stored is to use magnetoresistance, and this is the most common approach today
  - The ***anisotropic magnetoresistive effect***, which was discovered by Lord Kelvin in the 19th century
    - He found that in certain metals, such as nickel, there was an ~5% change in resistance depending on whether current flow was parallel or perpendicular to the direction of an applied magnetic field
  - The ***giant magnetoresistive*** effect was discovered in 1988
    - In this case, a stack of thin films of alternative magnetic and non-magnetic materials are used (e.g. Fe and Cr)
    - Electrical conduction through these superlattices were found to produce more pronounced changes in resistance than the anisotropic magnetoresistive effect

- The ***tunnelling magnetoresistance*** effect was discovered in the mid-1970s
  - In this case, two ferromagnetic materials are separated by a thin insulating layer
  - The quantum mechanical tunnelling of electrons between the two layers means that the resistance between the upper and lower contacts changes dramatically depending on the magnetic field passing perpendicularly through the structure

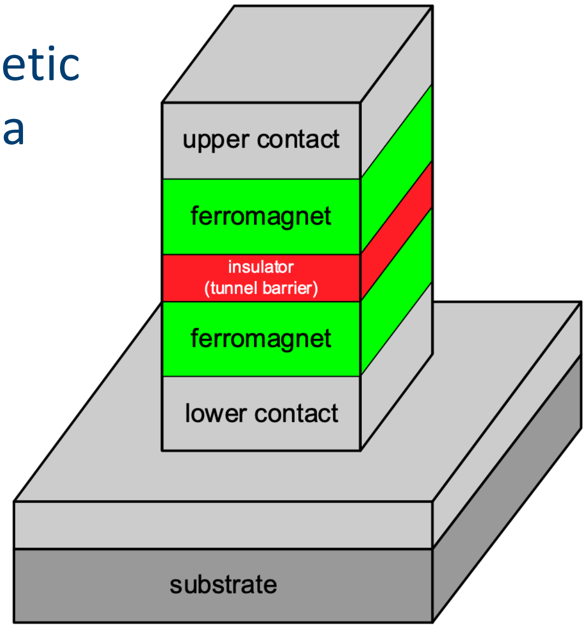
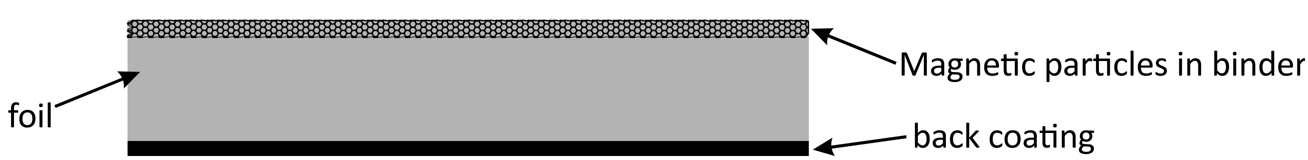


Image attributed to Fred the Oyster

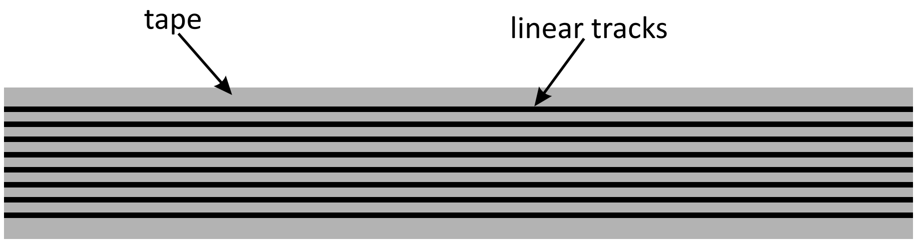
- All three magnetoresistive effects have been used over the years to produce read heads
  - Currently read heads based on tunnel magnetoresistance dominate (note that this particularly suits the orientation of perpendicular recording)
- In all magnetoresistive read systems, it is no longer the change in magnetisation between domains that is being measured (as with inductive reading) but the absolute magnetisation of each domain bit

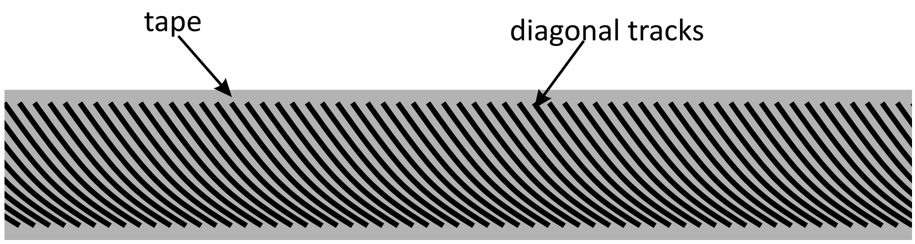
Magnetic Tape

- Magnetic tapes provide an alternative means of data storage
  - Very high data densities can be achieved but whereas a disk system allows a read/write head to be located at a particular point in milliseconds a tape has to be wound through to get to a particular point, taking many seconds
  - Tape remains an important technology for long-term data backup
- The structure of the tape itself is for there to be:
  - a flexible carrier foil which is not magnetic (e.g. plastics such as PET)
  - a magnetic material, which is often magnetic particles (e.g. Fe_2O_3, CrO_2) in a binder
  - a back coating to protect the foil



- Data is recorded along linear tracks that run end to end along the tape or in diagonal lines across the tape (a helical scan)
  - Helical scanning results in higher data densities but is more complex requiring a read/write head to be on a spinning disk which rotates faster than the tape moves





- Data is stored using longitudinal recording (the magnetic field vector points in the plane of the tape)
    - This allows a ring writing head to be used of similar basic construction to that used in the hard disk drive (Slide 14)
    - The same ring is usually used for reading as well using inductive coupling
    - As with the hard disk, it is the change in magnetisation between neighbouring domains that results in current being induced in the reading circuit