

### 3.15 Magnetic Fundamentals C.A. Ross, DMSE, MIT

**References:**

Jiles, Introduction to Magnetism and Magnetic Materials

**Magnetic quantities and units**

H = magnetic field, A/m –represents energy gradient, or torque on a dipole

B = magnetic flux density, T or Wb/m<sup>2</sup> –number of magnetic field lines per unit area

M = magnetization, A/m –the magnetic moment, the response of a material to a field.

H comes from a current:

current i produces tangential field  $H = i/2 \pi r$  at radius r

or from a magnetic material.

B depends on H: in free space

$$B = \mu_0 H \quad \mu_0 = 4\pi 10^{-7} \text{ Henry/m}$$

but inside a material

$$B = \mu_0 (H + M)$$

or

$$B = \mu_0 \mu_r H \quad \mu_r = \text{relative permeability}$$

or

$$M = H(\mu_r - 1)$$

or

$$M = \chi H \quad \chi = (\mu_r - 1) = \text{susceptibility}$$

M and B both indicate how a material responds to a field H. Lines of B are continuous.

Note the same relation expressed in cgs units:

$$B \text{ (Oersted)} = H \text{ (Gauss)} + 4\pi M \text{ (emu/cc)}$$

where

$$1 \text{ Oe} = (1000/4\pi) \text{ A/m} = 79.6 \text{ A/m}$$

$$1 \text{ G} = 10^{-4} \text{ T}$$

$$1 \text{ emu/cc} = 1 \text{ kA/m}$$

**Different types of materials**

Diamagnet: atom has no net magnetic moment, but a field induces a small moment opposite to the field. Susceptibility is negative ( $\mu_r < 1$ )

Paramagnet: atoms have a net moment but the spin directions are randomly arranged. An applied field can give weak alignment, hence a small susceptibility that varies with 1/T. ( $\mu_r > 1$ )

Ferromagnets have spontaneous magnetization, and a large permeability which depends on the history of the sample. Nonlinear, hysteretic behavior.

**Origin of magnetic behavior**

Angular momentum of electrons produces magnetization due to moving charges.

Magnetization comes from 1) electron spin, 2) electron orbital motion.

Contributions from paired electrons cancel out, so strong magnetic effects are found in materials with unpaired electrons.

One electron has a moment of  $1 \mu_B$  (Bohr magneton) =  $9.27 \cdot 10^{-24} \text{ Am}^2$

Stern-Gerlach and Zeeman experiments indicate the quantization of the magnetization in atoms.

We expect large magnetic effects in transition metals (unfilled 3d) and rare earths (unfilled 4f) because these can have a large net spin.

e.g. Fe<sup>3+</sup> has 3d<sup>5</sup>: expect  $5\mu_B$  per atom (neglecting orbital contributions)

Fe has 3d<sup>8</sup>: expect  $2\mu_B$  per atom

Ferromagnets have spontaneous ordering of the spins in neighboring atoms due to exchange coupling. If spins make angle  $\theta$ ,

$$\text{exchange energy} = A (1 - \cos \theta)$$

where A is the exchange constant, e.g.  $1.4 \cdot 10^{-20}$  J for Fe

Negative A gives antiparallel alignment: material is antiferromagnetic or ferrimagnetic.

Above the Curie temperature  $T_c$ , the spins are disordered,  $kT_c \sim A$ . (770°C for Fe)

Aligned spins form domains which usually point in different directions, giving no net moment to the sample. However, the domains can be oriented (i.e. the domain walls can be moved) by a relatively small field giving a large net moment, so the permeability is very high. The shape of the M-H curve is hysteretic; important loop parameters include area within the curve (the energy expended as the field is cycled back and forth) saturation magnetization (the magnetization in a large field) remanence (the magnetization remaining at zero field) coercivity (field needed to bring the magnetization to zero).

### Anisotropy and Domains

Magnetic energy consists of the following terms:

*exchange energy* (minimise by having all spins parallel)

*magnetostatic energy* (minimise by having domains pointing in different directions so there is no external field produced by the magnetic material)

*Zeeman energy* (potential energy due to an externally applied magnetic field,  $E = M \cdot H$ )

*magnetocrystalline energy* (lower if the magnetization is pointing in certain crystallographic directions, eg the c-axis in Co)

Domain structures form to minimise energy. Domains are typically microns or larger; domain wall widths  $\sim 100$  nm.

*Magnetocrystalline anisotropy* represents the energy needed to ‘pull’ the magnetization away from the preferred (easy) axis.

e.g.	Co	$K_u = 4.1 \cdot 10^5 \text{ J/m}^3$	uniaxial, [0001] is easy
	Fe	$K_1 = 4.8 \cdot 10^4 \text{ J/m}^3$	cubic, <100> is easy
	Ni	$K_1 = -4.5 \cdot 10^3 \text{ J/m}^3$	cubic, <111> is easy

Uniaxial: energy  $E = K_u \sin^2 \phi$   $\phi =$  angle between M and easy axis

Cubic:  $E = K_1 (\cos^2 \phi_1 \cos^2 \phi_2 + \cos^2 \phi_2 \cos^2 \phi_3 + \cos^2 \phi_3 \cos^2 \phi_1) +$  higher order terms  
 $\phi_i =$  angle between M and the i axis

Domain wall width is determined by a balance between exchange (favors wide walls) and magnetocrystalline anisotropy (favors narrow walls).  $a =$  lattice parameter

$$\text{wall width} \quad d = \pi \sqrt{A/2Ka}$$

$$\text{wall energy} \quad E_w = \pi \sqrt{2AK/a}$$

For small enough particles it is not worth establishing a wall because the savings in magnetostatic energy are less than the wall energy. These are ‘single domain’ particles.

Very small particles are thermally unstable because the net magnetic energy  $K_{\text{tot}} < 25kT$  (here V is the volume of the particle)

*Magnetostatic energy (a.k.a. self-energy or demagnetizing energy)*

The energy in the field surrounding the magnetized object depends on the way the object is magnetized. For instance, a long thin object has less magnetostatic energy if it is magnetized along its length, compared to across its length. This can be expressed in the same way as a uniaxial anisotropy: if the long axis is z and the short axis is x then

$$E = K_{\text{shape}} \sin^2 \phi \quad \phi = \text{angle between } M \text{ and } z \text{ axis}$$

where  $K_{\text{shape}} = 0.5(N_x - N_z) M_s^2$

The  $N$ s are called demagnetizing factors and depend on the shape of the object. For instance for an infinite cylinder with length in the z direction,  $N_z = 0$  and  $N_x = N_y = 0.5$ . The field inside the object along the i axis due to its own magnetization is

$$H_d = - N_i M_s \quad M_s = \text{saturation magnetization.}$$

### **Hard and soft materials**

In a soft material, walls are easy to nucleate (low energy, i.e. low A and magnetocrystalline anisotropy) and move (few pinning sites), magnetization is easy to rotate (low magnetocrystalline anisotropy).

Hard materials have opposite properties: high energy walls, pinning sites, high anisotropy, often made of single-domain particles.

### 3.15 Transformers and DC motors C.A. Ross, DMSE, MIT

**References:**

Braithwaite and Weaver, Electronic Materials, sections 3.2 and 3.3  
(Jiles, Introduction to Magnetism and Magnetic Materials 4.3.3 & 12.1.7)

**How do transformers work?**

Two coils wrap around a soft magnetic core. The input side has a varying current  $i_m$  through  $n$  turns of wire.

Ampere:  $\oint H \cdot dl = ni_m$

Within the core,  $B = \mu_o \mu_r H$

(Soft magnet: large, nearly constant  $\mu_r$ )

Put a secondary coil around the core:  $n'$  turns

Faraday  $V = -n' d\phi/dt$

where  $\phi = B \cdot A$  ( $A =$  coil area)

Now we draw a current from the secondary: current  $i_s$  induces a current  $i_p$  back in the primary. Now primary current is  $i_m + i_p$ .

Power transferred  $V_s i_s = V_p i_p$ , where  $V_s/V_p = n'/n$

Properties of the core:

- easy to magnetize to have a high  $B$
- high  $B_s$
- low hysteresis
- resistive to avoid eddy currents.

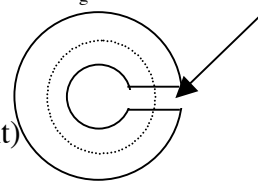
Soft magnetic materials

	$T_c / K$	$B_s / T$	$H_c / A/m$	$\mu_r$	$W, J/m^3$
Fe	1043	2.2	$\sim 4$	200,000	30
Fe-3%Si	1030	2.1	$\sim 12$	40,000	30
a-FeBSi	630	1.6	$\sim 0$	$>100,000$	15

**How do DC motors work?**

We characterize hard magnets by the  $(BH)_{max}$  product in the hysteresis loop. For the magnet to be able to do some useful work, it needs to produce some external flux, e.g. at the gap of a ring-shaped magnet with a cut made in it. Field  $H_g$  exists in the gap.

Ampere:  $l_m H_m + l_g H_g = 0$  around dotted line  
 also  $B_m = B_g$   
 $B_m = \mu_o \mu_r H_m$  (negative since in second quadrant)  
 $B_g = \mu_o H_g$   
 hence  $H_m = -l_g B_m / l_m \mu_o$



This linear relation intersects the hysteresis loop and defines uniquely the operating point.

The amount of work that can be done by the magnet is proportional to  $l_g H_g B_g$  so scales with the  $(BH)_{\max}$  product.

In a permanent magnet motor: a current  $i$  runs through a wire length  $l$  in a  $B$  field.

Force  $F = Bil$  (use Fleming's left hand rule)

This gives a force perpendicular to the wire and to  $B$ .

- A radial  $B$  is produced by two permanent magnets called the stator.
- The wire is wrapped round a vertical piece made of a soft magnet (the rotor). The purpose of the soft magnet is to concentrate the flux lines through the coil, giving maximum  $B$ .
- Current is supplied by a commutator (sliding contact).

Desirable properties of the permanent magnets: must stay magnetized despite their shape, and the fields produced by the wire, hence a high coercivity. Must produce large  $B$ , hence a high  $B_s$  i.e. high  $(BH)_{\max}$ .

Efficiency of motor is maximized if we can reduce the resistive losses in the wire. So minimize  $\rho/ABv$ , where  $\rho$  is resistivity,  $A$  is wire x-section and  $v$  is rotation velocity.

#### Hard magnetic materials

	$T_c / K$	$B_r / T$	$H_c / kA/m$	$(BH)_{\max}, kJ/m^3$
Alnico-5	1160	1.4	64	44
$BaO.(Fe_2O_3)_6$	720	0.4	264	28
SmCo5	1000	0.85	600	140
$Nd_2Fe_{14}B$	620	1.1	890	216
		remanence		

### 3.15 Data Storage C.A. Ross, DMSE, MIT

#### References:

Spaldin, Magnetic Materials (Cambridge Univ. Press, 2003), Ch. 11  
 Braithwaite and Weaver, Electronic Materials, sections 3.8-10, 3.12 and 3.3  
 Jiles, Introduction to Magnetism and Magnetic Materials Chap. 14

#### Magnetic Recording - Tape or hard disk recording system

##### *Writing by induction:*

a field is produced in the gap of the core, when a current flows through a wire wrapped round the core. The field writes data on the disk.

##### *Reading by induction:* (No longer used)

as the head passes over the fringing fields from the bits in the medium, the changing flux in the gap induces changing magnetization in the core which induces a voltage in the coil.

The medium is usually magnetized in plane. A change in magnetization direction (and the associated fringing field) represents a 1. No change in magnetization represents a 0.

Head materials: soft, high permeability, high saturation magnetization.

Permalloy, NiFe	$H_c \sim 4$ A/m	$B_s = 0.9T$	$\mu_r = 20,000$ (1000 @ 10 MHz)
Sendust, FeAlSi	$H_c \sim 5$ A/m	$B_s = 1.0T$	$\mu_r = 10,000$
FeN	$H_c \sim 100$ A/m	$B_s = 2.8T$	$\mu_r = 1,000$ best: highest $B_s$

##### *Media: Hard disk*

Al /NiP or glass substrate.

Longitudinal media: Cr underlayer with (200) texture.

CoCrPtTa... alloy with (1120) texture; grown at high temperature to obtain Cr segregation at grain boundaries so each grain is decoupled and acts as a single domain particle. Pt raises magnetocrystalline  $K_u$ .

Perpendicular media: now has largely replaced longitudinal media, capable of higher density recording. The c-axes of the Co alloy orient out of plane, guided by a Ti seed layer; soft underlayer is placed underneath to close the flux.

Carbon-nitrogen-hydrogen overcoat with perfluoroether lubricant.

2011 hard drives: >700 Gbit/in<sup>2</sup>, data rates of ~500 Mbit/sec.

*Tape:* PET substrate (polyethylene terephthalate)

$\gamma$ -Fe<sub>2</sub>O<sub>3</sub> (maghemite) particles in a polymer binder. Single domain; elongated for high coercivity, which is also raised by adding Co. This is a defect spinel structure (spinel is AB<sub>2</sub>O<sub>4</sub>, e.g. Fe<sub>3</sub>O<sub>4</sub>; A in the tetrahedral, B in the octahedral sites, fcc oxygen. Other particles have been used – CrO<sub>2</sub>, Fe, BaO-6Fe<sub>2</sub>O<sub>3</sub>

##### *Magnetoresistive readback*

Magnetoresistance of a magnetic material comes from the difference in scattering of spin-polarized electrons as they pass through the material. For example Fe has ...3d<sup>6</sup>4s<sup>2</sup> electrons. In the solid there are 2.2 more spin-up than spin-down electrons, oriented parallel to M. If M is parallel to the current, there is more chance of scattering so resistance is higher:  $\Delta R$  is small, e.g. 2% for permalloy (NiFe).

$$\text{Anisotropic magnetoresistance (AMR)} \quad R = R_0 + \Delta R \cos^2\theta$$

In a multilayer structure such as Co/Cu/Co/Cu..., Fe/Cr/Fe/Cr... or Co/Cu/NiFe, there is a larger effect called giant magnetoresistance (GMR). Scattering depends on the relative magnetization of adjacent magnetic layers: if parallel, the resistance is lower. This effect can be ~ 10%. It does not depend on the current direction, only on the relative magnetization of the layers.

GMR is used to make readback heads. A stack called a spin-valve is used: Antiferromagnet-Ferromagnet-Nonmagnet-Ferromagnet.

The AF pins the adjacent FM (the pinned layer). The other FM layer can rotate its magnetization in response to the fringing fields from the bits on the disk. The resistance of the stack depends on the angle between magnetization directions in the two magnetic layers, so is sensitive to the field from the disk.

The AF can be IrMn (FeMn and NiO are older options); the FMs are Co, CoFeB, or NiFe, and the nonmagnetic spacer is Cu (a spin valve) or MgO (or previously  $Al_2O_3$ ) (a tunnel junction). In the tunnel junction, resistance changes of 600% can be achieved in the best cases.

Magnetoresistance is an example of a coupling between magnetism and electronic properties. There are many devices being developed to use these 'magneto-electronic' or 'spintronic' phenomena, e.g. MRAM (magnetic random access memories).

### **Magneto-optical Media**

Magneto-optical properties such as Faraday rotation are examples of a coupling between magnetism and optical properties.

Kerr effect: polarized light is rotated on reflection from a magnetic material.

Faraday effect: polarized light is rotated on transmission through a magnetic material.

Kerr effects occur in all magnetic materials (Faraday effects also, if the material is transparent). Amorphous RE-TM alloys (rare earth – transition metals), e.g.  $a-(Tb,Gd)_x(Fe,Co)_{1-x}$  where  $x \sim 0.2$ , have large Kerr rotations and are used in MO disks. Other materials are Co/Pt multilayers.

The RE and the TM elements magnetize antiparallel so the materials are ferrimagnets. The magnetization of each group varies differently with temperature, so at some temperature the material is an AF because they exactly cancel. This is called the compensation temperature, and it is designed to be ~ 300K. At this point, the magnetization cannot be affected by an external field.

To write, a laser spot heats the disk locally and a global magnetic field reverses its magnetization (which is perpendicular to the substrate, due to deposition of the film in a field during manufacture). To read, a weaker laser is used and the Kerr rotation shows which way the spot is magnetized (up = 1, down = 0). The Kerr effect comes mostly from the TM atoms so is high even at the compensation temperature.

The disk is made of glass or plastic with dielectric/MO material/ dielectric/Al heatsink layer/protective coat.

**Optical media - CDs and DVDs** Track pitch 1.5  $\mu m$ , bit length 1- 2  $\mu m$ .

They look superficially similar to MO disks, but these rely on the reflectivity of a surface.

In CDs and DVDs bits are encoded as small pits which lower the reflectivity

Write-once media (WORM) uses Al films, Te alloys, organic dyes or semiconductors such as a-GaSb, where a laser permanently burns or melts the film to write a bit.

Phase change media is a rewritable version, where the reflectivity depends on refractive index which is affected by the cooling rate of the spot. Use Te alloys (fast cool – amorphous – reflective; slow cool – crystalline – less reflective). This can be rewritten many times.

## Compact Disk Optical Data Storage

A Compact Disc is made from a 1.2 mm thick disc of almost pure polycarbonate plastic and weighs approximately 16 grams. A thin layer of aluminium or, more rarely, gold is applied to the surface to make it reflective, and is protected by a film of lacquer. The lacquer is normally spin coated directly on top of the reflective layer. On top of that surface, the label print is applied. Common printing methods for CDs are screen-printing and offset printing.

CD data is stored as a series of tiny indentations (pits), encoded in a tightly packed spiral track molded into the top of the polycarbonate layer. The areas between pits are known as "lands". Each pit is approximately 100 nm deep by 500 nm wide, and varies from 850 nm to 3.5  $\mu\text{m}$  in length.

The spacing between the tracks, the pitch, is 1.6  $\mu\text{m}$ . A CD is read by focusing a 780 nm wavelength semiconductor laser through the bottom of the polycarbonate layer. The change in height between pits and lands results in a difference in intensity in the light reflected. By measuring the intensity change with a photodiode, the data can be read from the disc.

The pits and lands themselves do not directly represent the zeros and ones of binary data. Instead, Non-return-to-zero, inverted (NRZI) encoding is used: a change from pit to land or land to pit indicates a one, while no change indicates a zero. This in turn is decoded by reversing the Eight-to-Fourteen Modulation used in mastering the disc, and then reversing the Cross-Interleaved Reed-Solomon Coding, finally revealing the raw data stored on the disc.

While CDs are significantly more durable than earlier audio formats, they are susceptible to damage from daily usage and environmental factors. Pits are much closer to the label side of a disc, so that defects and dirt on the clear side can be out of focus during playback. Discs consequently suffer more damage because of defects such as scratches on the label side, whereas clear-side scratches can be repaired by refilling them with plastic of similar index of refraction, or by careful polishing.

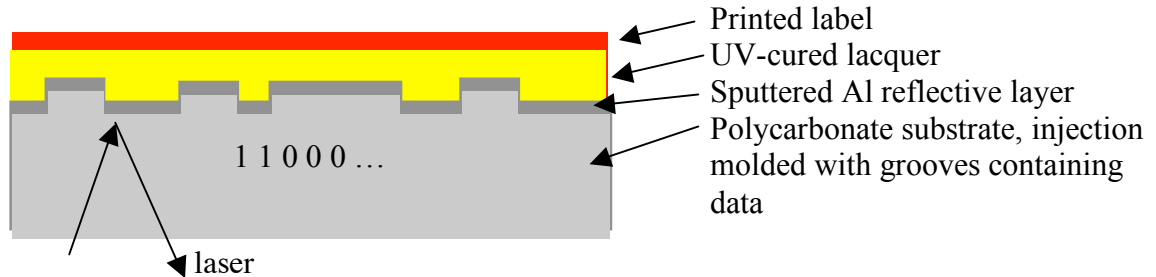
\* Scanning velocity: 1.2–1.4 m/s (constant linear velocity) – equivalent to approximately 500 rpm at the inside of the disc, and approximately 200 rpm at the outside edge. (A disc played from beginning to end slows down during playback.)

- \* Track pitch: 1.6  $\mu\text{m}$
- \* Disc diameter 120 mm
- \* Disc thickness: 1.2 mm
- \* Inner radius program area: 25 mm
- \* Outer radius program area: 58 mm
- \* Center spindle hole diameter: 15 mm

The program area is 86.05  $\text{cm}^2$  and the length of the recordable spiral is  $86.05 \text{ cm}^2 / 1.6 \mu\text{m} = 5.38 \text{ km}$ . With a scanning speed of 1.2 m/s, the playing time is 74 minutes, or around 650 MB of data on a CD-ROM. (*All text is copied from Wikipedia*)

## Structure of Optical Disks

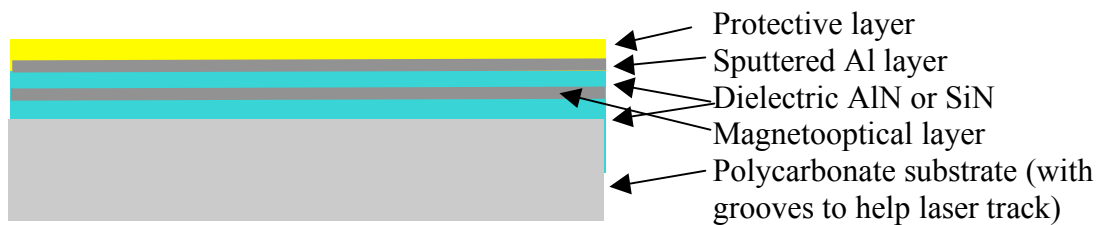
### Read-only structure of CD or DVD (drawn along track)



Optical path difference between pit and land (flat region)  
 = refractive index of polycarbonate x 2 x depth of pit,  
 is chosen to be  $\lambda/2$  to get max. contrast in reflectivity.

### Rewritable Magneto-optical disk

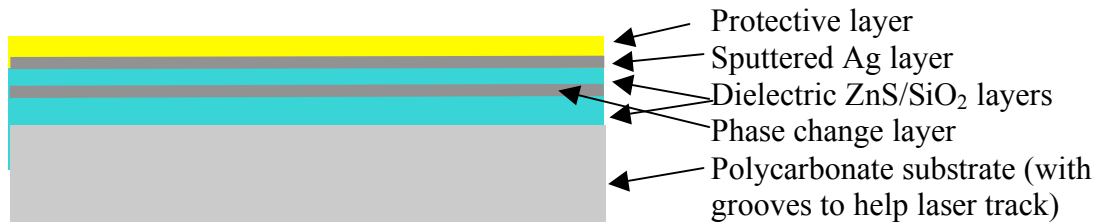
Al acts as heat sink and raises Kerr rotation by helping trap light



### Rewriteable optical disk

Thermally-induced change in crystal structure of phase-change material leads to a variation in refractive index and absorption; ensure total difference in path length of  $\lambda/2$  to get maximum contrast in reflectivity. Change between amorphous and crystalline is controlled by temperature vs. time relation.

Ag acts as reflector and heat sink.

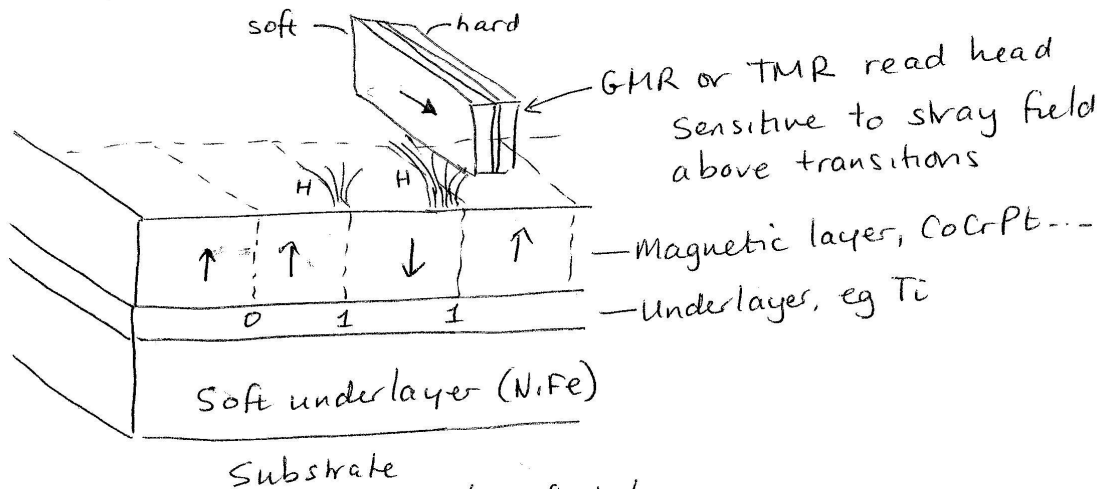


### Write-once optical disk

Replace the dielectric/phase change/dielectric stack with a layer of dye that can be damaged by a high intensity laser pulse to make the bits.

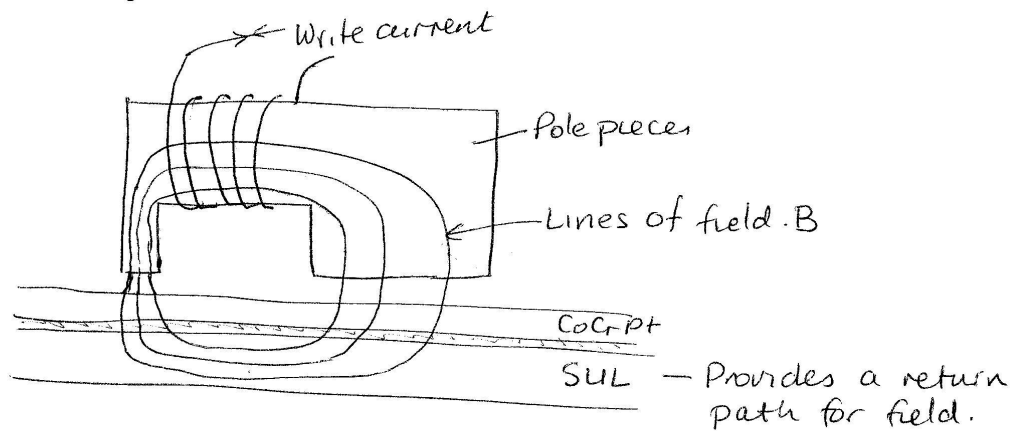
## Perpendicular Media

Hard disks now use a film with perpendicular magnetization, obtained using an underlayer to help the cobalt c-axis orient out of plane.



It enables a higher density of data.

Write using an inductive head:



↑  
writing occurs in CoCrPt  
where field is strongest.