Q1 Band diagrams & quantum dots

Part (a)(i) Well answered.

(a)(ii) Most candidates could draw defect band and explain E/k conservation well.

(a)(iii) Some confusing diagrams, but most candidates showed double heterostructure and got emission wavelength right (band gap of GaAs given in data book).

(a)(iv) Well answered.

(b)(i) Some quite confusing or not precisely defined answers.

(b)(ii) Most candidates got to confinement in 1D, some did not consider actual QD band gap with confinement of both holes and electrons.

(b)(iii) Generally well answered, some not describing set-up to measure rather explaining only D dependence.

Q2 Semiconductor properties & device design

(a)(i) Heavy hole generally correctly identified, but some not so precise explanations of effective mass.

(a)(ii) Generally well answered.

(b)(i) Well answered, with many detailed responses.

(b)(ii) Less well answered compared to high-k case, some confusion on low-k design.

(c) Many detailed CNT descriptions, most focussing on CMOS Via application.

(d) Many good answers, some neglecting flexibility demand.

Q3 Piezoelectric actuator

Most candidates could answer parts (a) and (b) well. Some candidates misinterpreted b(i) as meaning the simplification was the assumption of no external electric field, however this was stated in the question as a condition.

In part (c) many candidates failed to identify that the actuator was operating in shear mode, this was slightly surprising given that sideways movement was clearly stated. Partial marks were awarded where answers to subsequent questions were in part wrong due to misidentifying the mode of operation. Few candidates appreciated that the overvoltage would have the potential to pole the ferroelectric in a different direction changing the mode of operation of the actuator from shear to thickness mode.

Q4 Soft and Hard Magnetic Materials

This question was well answered on the whole. Some candidates attempted to argue that magnetic materials other than NdFeB and SmCo could work at N=0.5 . This may have been due to their not looking at both charts of properties in the data book.The answer to (c)(iv) was quite sensitive to a range of reasonable assumptions and full marks were awarded if the answer was justified and the candidate had used a reasonable assessment of the point where demagnetization would occur.

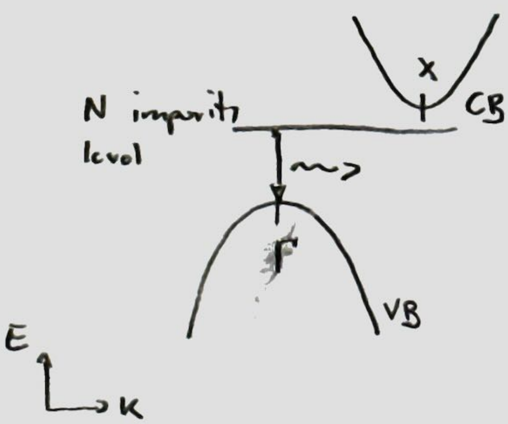
Q1 (a) (i) Efficient light emission requires a direct band gap, i.e. the conduction band minimum to also be at Γ point. This is given up to a P fraction of ~ 0.45, corresponding to band gap of ~ 2eV.

Hence the minimum λ of light emitted is given by

$$E = \frac{hc}{\lambda} \rightarrow \lambda = \frac{hc}{E} = 620 \text{ nm}$$

This corresponds to orange/red colour. [10%]

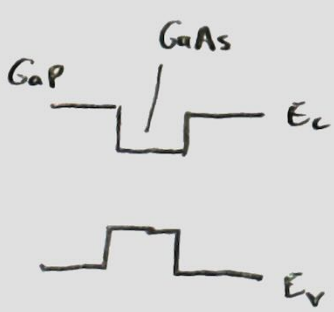
(ii) If we add Nitrogen impurity, which enters the Phosphorus site, it will form a localised impurity level, see figure.



This makes a quasi-direct gap for transitions from the N level to the valence band. Note that the N level is extended in k due to localisation in x and thus Heisenberg uncertainty. This allows E and k/p conservation.

[15%]

(iii) Type-I band alignment allows double heterostructure formation:



This would allow e and h to be trapped in quantum well like structure.

Laser wavelength will be that corresponding to band gap of GaAs, i.e. 1.4 eV

$$\lambda = \frac{hc}{E} = 886 \text{ nm}$$

[15%]

(iv) Challenge in hetero engineering is lattice mismatch which will lead to strain and interfacial dislocations / defects. For 2D materials this can be avoided as stack bonding is only van-der-Waals. Also small diameter 1D nanowires can address this, as they have small interface footprint. [10%]

Q1 (b) (i) Exciton Bohr radius is average distance between an electron and hole

$$a_{Bx} = \frac{4\pi\varepsilon\hbar^2}{m_0 e^2}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right)$$

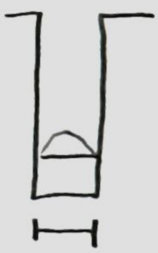
(this formula not required, comes from hydrogenic model)

The exciton Bohr radius is dimension below which quantum confinement effect will come into play.

Order of magnitude is 5-10 nm.

[10%]

(ii) Start with 1D infinite potential well, and consider ground state E:



$$n\frac{\lambda}{2} = a \rightarrow \lambda = \frac{2a}{n}$$

$$p = \frac{h}{\lambda} = \frac{hn}{2a}$$

$$E = \frac{p^2}{2m} = \frac{h^2 n^2}{8 m a^2}$$

$$\rightarrow E_0 = \frac{h^2}{8ma^2}$$

for 3D (each direction independently), adding effective mass and $D = a$

$$\rightarrow E_{well} = \frac{3h^2}{8 m_0 m^* D^2}$$

Quantum dot band gap:

$$E_{gap} = E_{gap}(\text{bulk}) + E_{well}^*$$

$$= E_{gap}(\text{bulk}) + E_{well}(e) + E_{well}(h)$$

$$\sim \frac{1}{D^2}$$

[30%]

Q1 b) (iii) Quantum dot diameter can be extrapolated from emitted photon energy, ie colour seen when optically pumped. Hence shine light on QDs with energy larger than their band gap and observe light emitted.

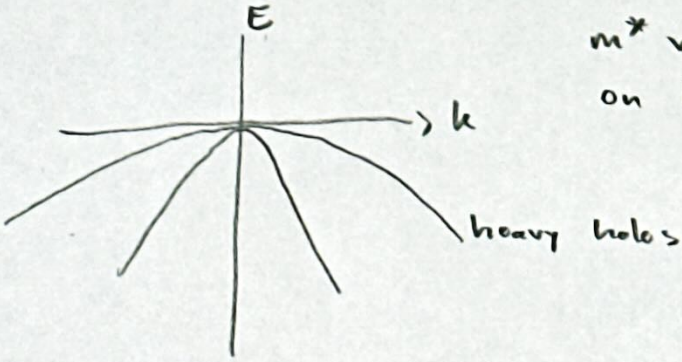
[10%]

Q2 (a) (i) Effective mass is concept to include effect of periodic crystal in carrier behaviour.

For parabolic band edges

$$m^* = \hbar^2 \left(\frac{d^2E}{dk^2} \right)^{-1}$$

and then allows use of Newtonian formulas with mass replaced by $m_0 \to m^*$.



m^* varies for e and h depending on band dispersion.

[15%]

(ii) For drift transport, carrier mobility $\mu = \frac{e\tau}{m^*}$

where τ is mean free time between collisions.

This comes from simple scattering model.

Thus higher m^* means lower μ, vice versa.

For Si under compression, a light hole band with lower m^* dominates, hence gives larger μ.

[15%]

(b) (i) Motivated eg by FET mutual conductance, transistor performance requires to keep gate capacitance high. For scaled devices based on SiO_2 the issue is that below a certain thickness there will be leakage due to tunnelling. Hence given that $C \sim \frac{\varepsilon}{d}$ idea for high-k material is to have high ε/k so that equivalent d can be thicker and thus prevent tunnelling.

Q2 (b) (i) Examples of high-k oxide materials include ZrO_2 and HfO_2. These are deposited via atomic layer deposition (ALD), which breaks down a CVD reaction into 2 self-limiting reaction, so that ultra-thin, conformal films can be reliably produced.

[20%]

(ii) low-k dielectric are in demand for FET interlayer separation and passivation. Idea is to prevent crosstalk / coupling. low-k design can include materials with low polarizability, like organo-silicon polymers, and porous structure (low k because of free volume/air).

[20%]

(c) Carbon nanotubes (CNTs) are highly interesting eg for vias / interconnects or as channel for scaled transistor design. For the former, CNTs offer highest current carrying capacity, and they should be metallic. This means eg only "armchair" type single-walled CNTs or the growth of multilayer CNTs. In both cases a high density is required. Integrated growth and contacting CNTs are main challenges for this. A good answer gives an informed discussion from various angles. For transitor channels, only semiconducting SWNTs need to be produced and contrallably contacted.

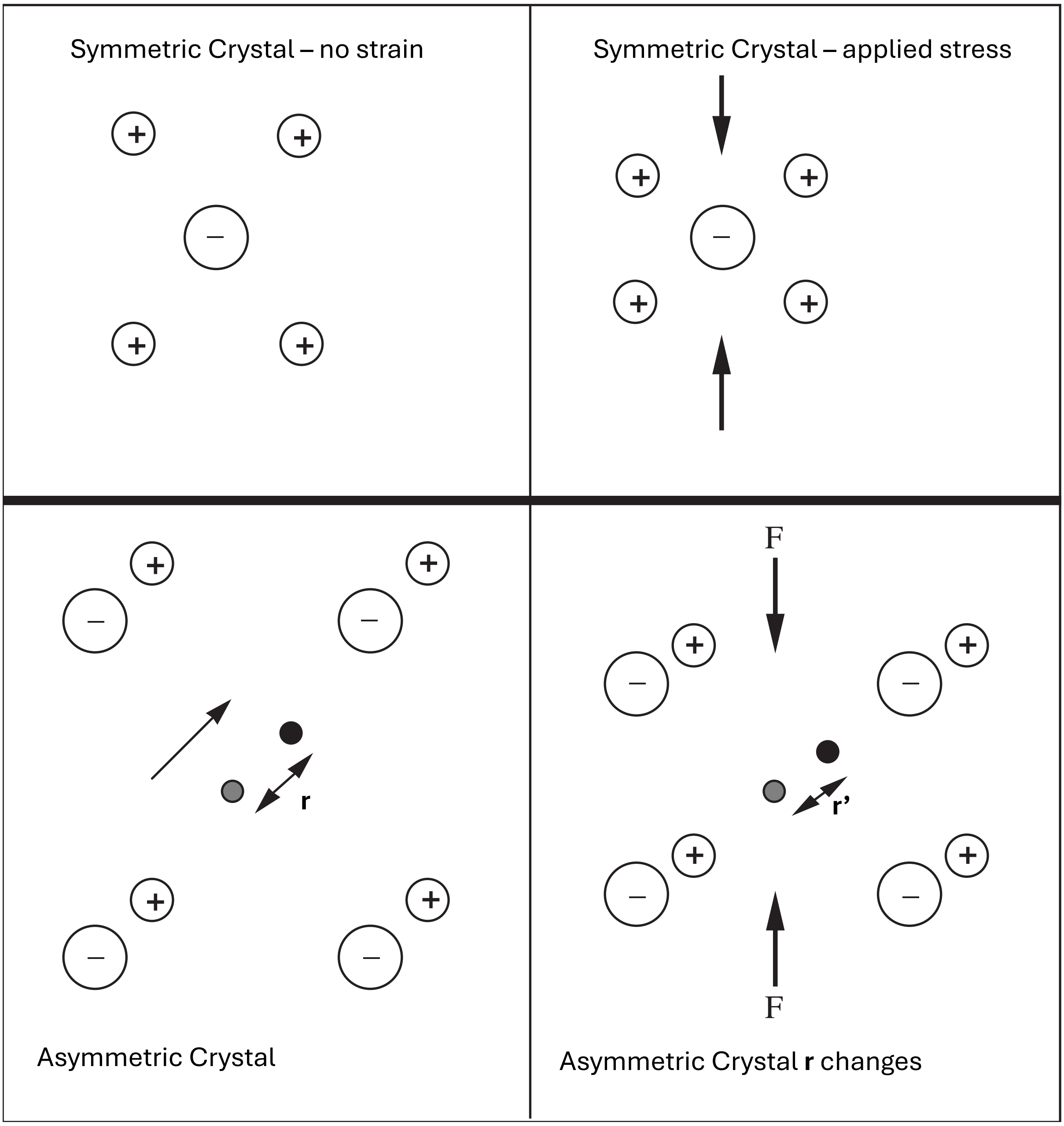
[15%]

(d) A possible design solution is to use 2D materials, which give transparency and flexibility due to their thinness. SC channel eg MoS_2, h-BN dielectric, graphene layers as contacts. Other solutions can be eg based on 1D tubes / wire networks.

[15%]

3) a) For an ionic crystal to be piezoelectric it must lack a centre of symmetry. This means that under applied stress, for example, the crystal strains and the centre of the positive ions and centre of negative ions become displaced with respect to each other. This then leads to a net charge appearing on the crystal surfaces.

[There is one crystal class which has no centre of symmetry but where the piezo effects cancel '432 / Gyrodial' but students are not expected to remember this]



The pyroelectric effect arises from two mechanisms: one is thermal disorder reducing the polarisation of a material with increasing temperature. The second is the distortion of the crystal structure due to thermal expansion changing **r** and thus the polarisation. Both these mechanisms, however, require the crystal structure to be polar which means it cannot be centrosymmetric.

A piezoelectric material, however, might only exhibit polarisation under stress and have no intrinsic dipole and thus exhibit no pyroelectric effect.

[15%]

b) i) The simple equation neglects the fact that the piezoelectric properties of a material are directional . Consequently, stress in a particular direction can couple to polarisation in all directions. To represent a piezoelectric material's properties properly a Tensor must be used which relates the Electric field vector to the stress or strain tensor. This would be expressed as :

$$P_{\mathrm{i}} = d_{\mathrm{ijk}} \, . \, \sigma_{\mathrm{jk}}$$

However as, in the stress and strain tensors the shear components are mirrored it is possible to use a reduced notation where subscripts 1-3 are used for tensile stress/strain and 4-6 for the three shear directions. This gives the following

$$\begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{pmatrix}$$

Which can also be written as $P_{\mathrm{i}} = d_{\mathrm{ij}} \, . \, \sigma_{\mathrm{j}}$ and $S_{\mathrm{j}} = d_{\mathrm{ij}} \, . \, E_i$ for the converse effect.

[15%]

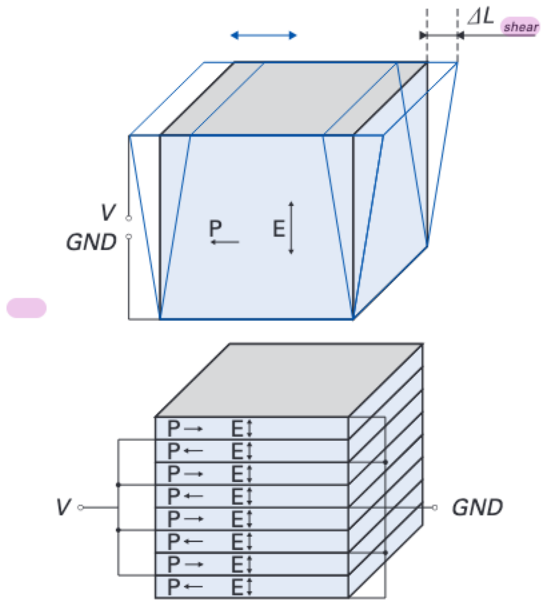
ii) If a thin sheet of a piezo material is used then a large electric field or strain is only developed across the thickness. In addition practical piezo materials are used in the form of poled ferroelectrics with the axis of polarization aligned in one direction.

This means that only E_3 and σ_3 are significant. This then results in only the piezo coefficients $d_{31} = d_{32}$, d_{33} and $d_{15} = d_{24}$ being non-zero.

The piezo electric mode of operation is thus defined by which piezoelectric coefficient is being exploited. For $d_{31} = d_{32}$ and d_{33} the charge is collected in the polarisation direction and the mechanical force is applied either along (d_{33}) or perpendicular (d_{31}=d_{32}) to the polarisation direction. For "shear mode" $d_{15} = d_{24}$ the electrodes are on an axis perpendicular to the polarization and on displacement is in shear.

[10%]

c) i) Here the movement of the stack is perpendicular shear to the direction of application of electric field. This is thus a "shear mode" 24 application . For shear mode the piezoelectric ceramic must be poled in plane as is shown in the manufacturers catalogue entry for this actuator:



[10%]

ii) From the converse piezoelectric effect we know that $S=d_{24}$ E. There are 12 layers so we can start by thinking about a single layer. To get 1.5 micron of displacement overall we need each to achieve 0.125 microns of displacement in each layer. From the definition of shear strain this is 0.125 / 500 = $2.5\text{x}10^{-4}$ or 250 microstrain . The electric field is $250/5\text{x}10^{-4}$ which is 500000 V/m .

We can then determine that the value of the piezoelectric coefficient as S/E must be 500 pC/N which is close to the manufacturers data sheet value for this material.

[20%]

iii) Here we are considering the direct effect. So $P=d_{24}\sigma$.

We need to multiple by area of the top of the plate (which is both the area of the electrode and the relevant area for calculating shear stress) to get that $Q= d_{24}$ F .

We can then recall that Q=CV for a capacitor and rearrange to get $CV=d_{24}F$ and finally that $F=CV/d_{24}$.

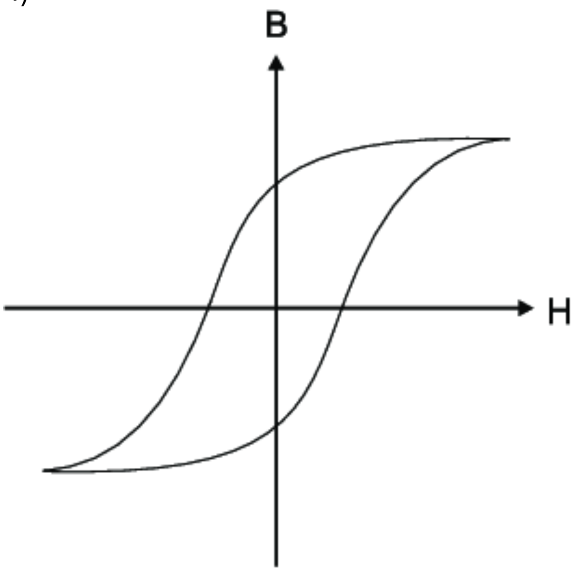
Plugging the relevant number in for one plate (since the force is the same in each plate) gives $0.125\text{x}10^{-6}$. 250 / 500 $\text{x}10^{-12}$. This gives 62.5 N.

[20%]

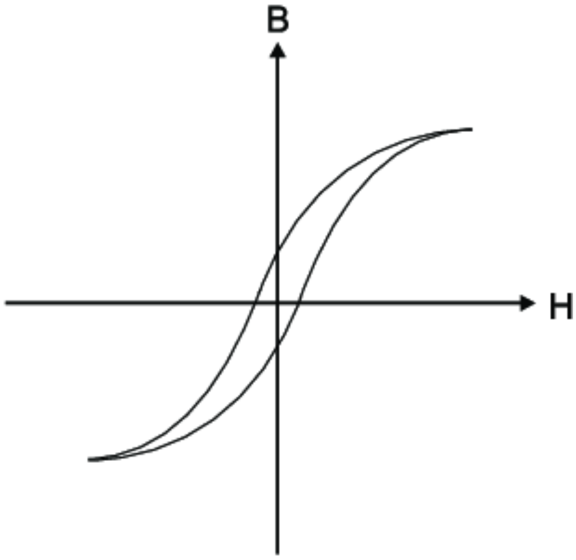
iv) As the material is ferroelectric a large voltage will pole the layers pointing between the electrodes rather than at right angles to them, so the polarization direction becomes vertical. The stack will then act in d_{33} mode – thickness and applied voltage will now result in a vertical rather than sideways displacement of the actuator. This characteristic is often the limitation on performance of shear actuators- if too much voltage is applied they become thickness mode actuators !

[10%]

4)



Hard Magnetic Materials



Soft Magnetic Materials

The “hardness” of a magnetic material relates to the difficulty in reversing the magnetisation. It is given by the size of the coercive field, defined as the applied H field required to make B zero.
Hard magnetic materials are used as permanent magnets as they remain magnetised. Permanent magnets are used in applications usch as fridge magnets, permanent magnet motors , magnetic separation devices and for mechanical clamping.

Soft materials are used in applications where a material with a large magnetic permeability is required, such as in transformers or inductors. They allow an inductor of a particular value to be much more compact than the equivalent air-cored version and transformers to be useably compact.
Soft magnetic materials are primarily used in inductors and transformers but also in data storage media such as hard discs. As was magnetic tape was a significant application however this has reduced in recent years as flash memory has taken over. Some use remains for archival digital storage on tape.

[15%]

b)i)
The requirement for an electrical steel is higher resistance (to suppress eddy current losses) and lower Hc to reduce core lossess. To this end electrical steels are processed to have very large grains to reduce grain boundary pinning of domains. They are foten alloyed with silicon as the principle alloying element rather than carbon as this reduced the conductivity without too rapid a deleterious effect on the magnetic saturation and permeability.

[15%]

ii) At 50 Hz the increase in resistance achieved by introducing silicon and the fact that core losses are still significant means that electrical steels are a reasonable choice. At very high frequencies the eddy current losses, which scale with the square of the frequency, become far too large for steel to be usable. At high freuqnecies the only plausible choice of soft magnetic material are the ceramic ferrite soft magnetic materials as they have very low conductivties.

[10%]

c)i) Starting from $B=\mu_o(H+M)$ we can substitute the equation for the demagneisation field (assuming no externally imposed fields) to get:

$$B=\mu_o M(1-N)$$

We can then multiply by H=-MN to get

$$BH=\mu_o M^2 N(N-1)$$

Magnetic field energy is proportional to BH so we can see where this expression is at a maximum by taking the derivative:

$$dBH/dN = \mu_o M^2 (2N-1)$$

This is minimised for N=1/2 . **[20%]**

ii) Iron has a very small coercive field. Candidates are not expected to remember this exactly but its as small as 0.1 kA/m . The demag field at N=0.5 assuming that iron has a magnetisation $\mu_o M$ of roughly 1T is 800 kA/m clearly the iron would have long demagnetised ! **[10%]**

iii) To achieve a shape factor of a half we need to consider the load line which is given by

$$\frac{B}{H} = -\mu_0 \frac{1-N}{N}$$

For N=0.5 this is simply a slope of -mu0.

This is shown superimposed on the characteristics of materials shown in the databook below. Clearly Ferrite (some grades), SmCo and NdFeB are fine – other materials are not.

[10%]

Fig 2a

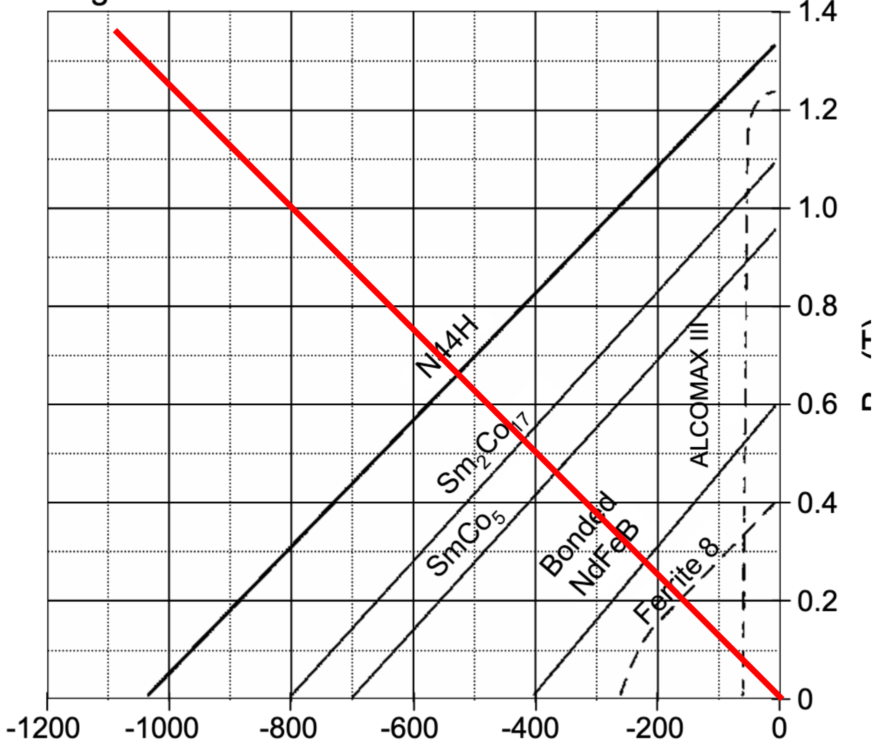
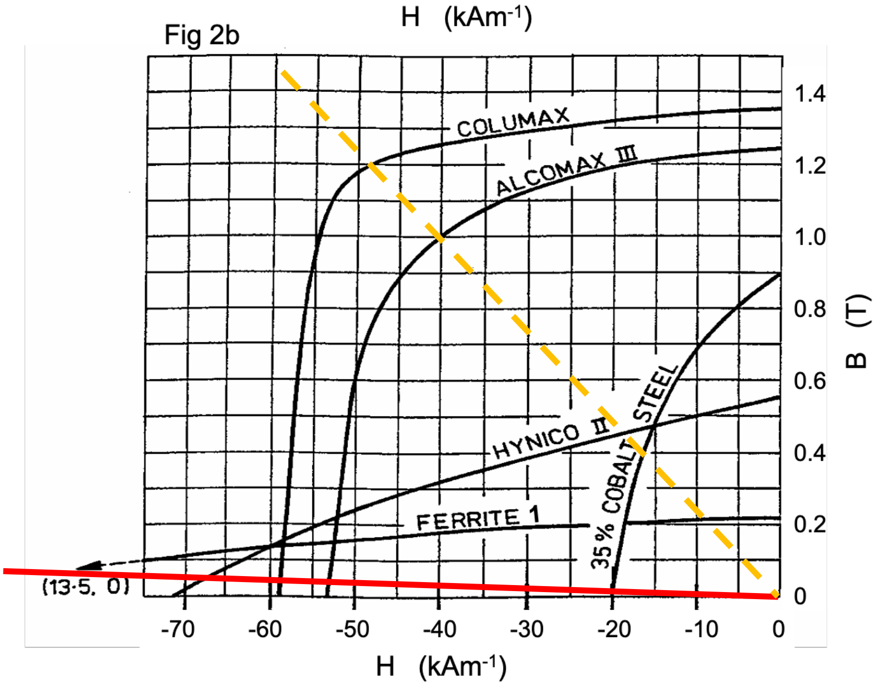


Fig 2b



iv) Looking at the data book the orange dotted line shows the likely largest N possible before demagnetisation becomes a problem. This line passes through 1 T and -40 kAm-1 which gives a slope of 2.5 x10^{-5} dividing by mu 0 gives about 19.

Rearranging (1-N)/N get us 19=(1/N-1) then 20=1/N so N is roughly 0.05. This roughly a long rod with l/d of 10.

[20%]