4C3 Crib 2021 – J.H Durrell/S. Hofmann

Q1

The question did not seem to pose specific problems. Part b) was the least well answered, relatively few candidates were able to propose more than one reason for the distortion. Part d) provoked some thoughtful and inventive answers, although some to part ii) were rather off-beam.

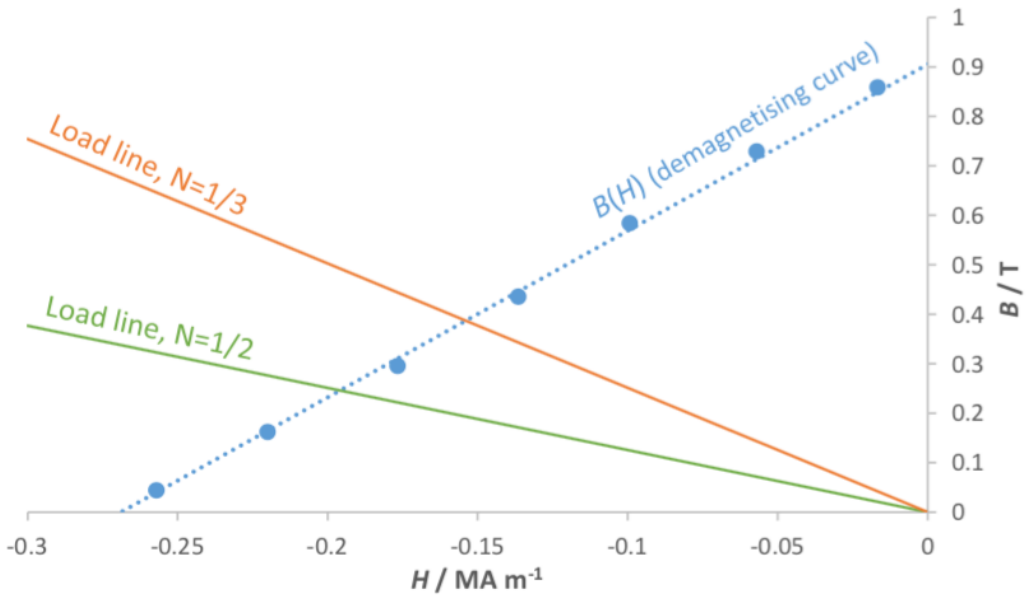
1)a) *This was not explicitly discussed in the notes however it can be answered using concepts taught in the course.* This question was someone binary in the performance of candidates. *Those that realised that the wide range of processing available in steel meant the pinning of domain walls could be tuned answered well.*

In the limit of soft iron with large grains we have an ideal soft (albeit DC only) magnetic material. However, just as with its mechanical properties, the rich range of available processing and alloying available to use allows to take this soft material and make it much harder, albeit much less hard than many modern materials. Additionally, Iron has a large Bsat and this is unaffected by processing and is retained with much alloying.
A Hard material needs to pin magnetic domain boundaries effectively, in the case of steel this can be achieved by processing to give small grains with lots of grain boundaries and with suitable alloying to provide precipitates. Steel alloys were at one point the best available permanent magnet material.
A key further consideration is that Steel is cheap and readily available, a practical consideration that should not be underestimated.

b) *One example of this is provided in the notes, reproducing that was not sufficient for full marks. This was the least well answered section of the question.*

The distortion occurs because the signals are coupled via the hysteresis curve of the core material. There are multiple ways in which this can give rise to distortion:
A material with a very “square” loop or one with a curve which has a minimal linear region will give rise to distortion. The response needs to be reasonably linear over the operating range.
A less extremely shaped response, yet where there is a large hysteresis, i.e. too large a coercive field, will also lead to distortion.
If the material has a small B_{sat} then it is possible to saturate the core leading to clipping of the output signal even if the response is not “square”. This is why, for example, Type AC RCDs fail to operate if there is a DC leakage current present – the current transformer is saturated.

c) *To answer this question candidates needed to combine what they know about demagnetisation and magnetic behaviour*. *Most candidates correctly answered this question.*
This is most conveniently achieved by plotting the line corresponding to the value of N B/H=-mu0 (1-N)/N (which can be easily derived from first principles by candidate if required) on to the B-H characteristic of the material the magnet is made of.



This allows us to determine the operating point of the magnet.
Once we have the operating point we can read off the B field we expect at the surface of the magnet from the y axis.
To determine the (BH) energy product we can combine this with the H field corresponding to the same point and multiply them together. Candidates may recall that (in free space or in a linear material) the energy density in a magnetic field is simply 0.5 the product of B and H. Note this is not (BH)max , which is only obtained if the operating point is determined for N=1/2 - this is only the case for certain shapes.

d)
This question was generally well answered, although some candidates chose ALNICO for i) for which 1917 is too early and some of the suggestions in ii) of ways to avoid demagnetisation were quite complex and off beam. Almost all candidates realised that horseshoes could be dispensed with for modern NdFeB and SmCo materials due to their large coercive field.

i) The evidence presented in the question points to the permanent magnets being made from a material with a low coercive field. This should link with the course where before the development of Co-Steel in ~1917 the alloys used were tempered C Steels with Cr or W addition that had rather low coercive fields. This means the magnets slowly demagnetise and, if removed from the magnetic circuit the increased self field will cause them to demagnetise completely.

ii) To avoid spontaneous demagnetisation it is important to maintain a magnetic circuit between the poles of the horseshoe magnet. A soft magnetic material placed externally would serve to minimise the demagnetisation field experienced by the magnets. Indeed in practice this is how such magnetos were dismantled.

iii) Alnico, NdFeB or SmCo would have significantly larger Hc and much larger remanent fields. Hard ferrites would likely provide enough field and have the advantage of cheapness. In an engine environment NdFeB might well be ruled out due to its low practical upper operating temperature of ~150 degrees C.

Q2

Generally well answered and the most popular question. Candidates seemed more comfortable with parts b) and c) than a) . Part a) required some thought and interpretation of taught concepts while parts b) and c) were more straightforward. A number of candidates assumed shear mode with a suitable choice of aspect ratio in part c) i) . As the question proved not sufficiently clear that the intended geometry was square (it was intended that shear operation be dismissed without calculation on grounds of practicality) where candidates made assumptions that led to shear mode being superior, they were marked correct.

A)

Not all candidates correctly identified that the loss is primary due to the rotation of dipoles, those that did answered well.

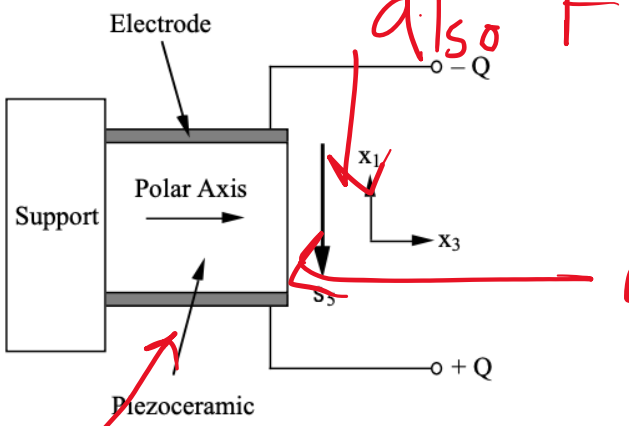
i) This resistance arises largely due to the dielectric in the capacitor. For a non-polar material induced dipoles are formed. For a polar dielectric dipoles must rotate . This movement generates heat – thus there is dissipation in the capacitor.
This loss is per AC cycle – so nothing to do with what you would measure with a DMM.
In practice this is what gives rise to the loss tangent / Equivalent Series resistance in a capacitor but explicit knowledge of those terms or complex plane interpretation is not required for marks.

ii) This question was challenging as it required some thought about the concepts that were taught in the course. Relatively few candidates clearly identified the primary advantage the ferroelectric materials can have very large permittivities.

Candidates should show that they understand that a ferro electric material will also exhibit piezo effects. These effects are in addition to the losses arising in any polar material.
So problems are that such a capacitor will exhibit losses due to ferro-electric hysteresis (as in a ferromagnetic core), some mechanical losses due to the piezo-electric effect – it is possible that the pyroelectric response of the capacitor may also add to noise. However, while these are all negative such capacitors are widely used, this is because the key parameter, dielectric constant, is very large allowing the highly compact capacitors we need in our phones.
Not covered in course - Capacitor “singing” is a known problem which can lead to failure of solder joints etc.

b) i) *This question required discussion – not simply replication of diagrams of modes from notes. Some candidates did not clearly make the point that the different modes are coupling of charge release and strain in different directions.*
Candidates should be able to clearly explain that as each coefficient links strain in a particular direction to charge release in another direction it follows that how the element needs to be arranged depends on this. Mode choice will depend on practical considerations (such as the space available in a watch), on the material (a material might exhibit a large d in one particular direction and we may wish to get the largest response), and disentangling other effects such as independence from pyroelectric effects exhibited by shear mode devices.

ii*) Of the three modes this is the one <u>not worked through</u> in the notes, although an outline sketch is provided. Candidates needed to apply what they have learnt in respect of the other modes to flesh this out. Simply providing an equation was not sufficient.*



$\sigma_5 = \frac{F}{a}$

$P = d_{15}\sigma_5$

$\frac{Q}{A} = d_{15}\frac{F}{a}$

$Q = \frac{d_{15}FA}{a}$

Correct identification of area + components required

c) I)

Some candidates correctly identified that shear mode could require a lower force than thickness if it was assumed the element was not square. Those candidates that reasonably argued this were marked correct.

This material has a very low d_{31} and the shape given does not have a large aspect ratio, consequently operation is in thickness mode (shear mode is complex to arrange and d_{15} is lower).

Ii) *This question was well answered in general. Where candidates assumed shear mode and correctly used the equations taking into account aspect ratio full marks were awarded. Where candidates assumed shear mode but made some errors in this section partial marks were awarded.*

From definition

Change in polarization $\Delta \hat{P} = \frac{\Delta Q}{A}$ — ΔQ: Charge released; A: Area

From definition of piezo effect

$\Delta \hat{P}_3 = d_{33} \Delta \hat{\sigma}_3$ → stress change

d_{33}: piezoelectric coefficient linking P in 3 and σ in 3

also $\Delta \hat{\sigma}_3 = \Delta F_3 / A$

so: $d_{33} \Delta F_3 = \Delta Q = C \Delta V$ (1)

rel. permittivity | electric constant | from definition of a capacitor

(2) $C = \varepsilon \varepsilon_0 A / t$ — t – thickness

Combining (1) + (2)

$$\Delta F = \frac{\varepsilon \varepsilon_0 A}{t} \frac{\Delta V}{d_{33}}$$

$$\Rightarrow \frac{170 \times 8.85 \times 10^{-12} \times 2 \times 10^{-6} \times 6000}{1 \times 10^{-3} \times 51 \times 10^{-12}}$$

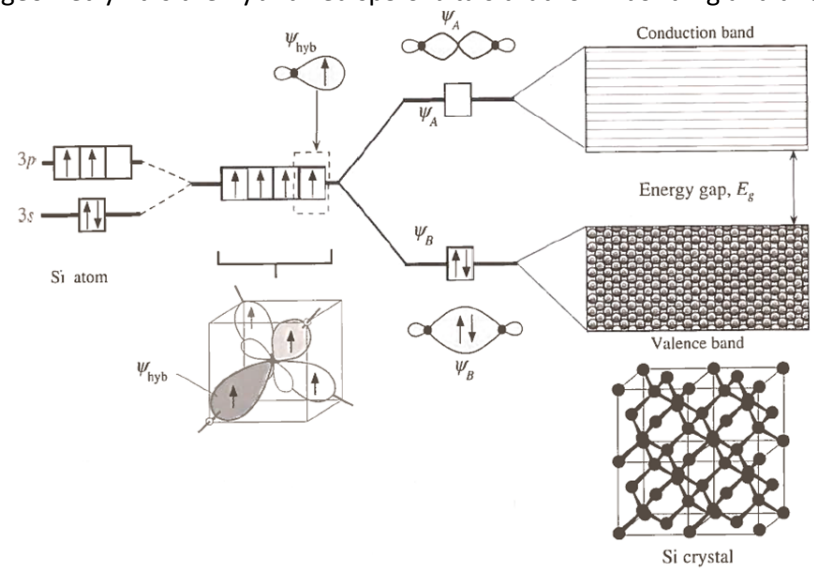
$$= 354 \text{ N}$$

While the equation above gives the numeric value 354 N, a 3 s.f. answer is not justified by the input data so we can state the answer as being 350 N (2 s.f.).

Q3

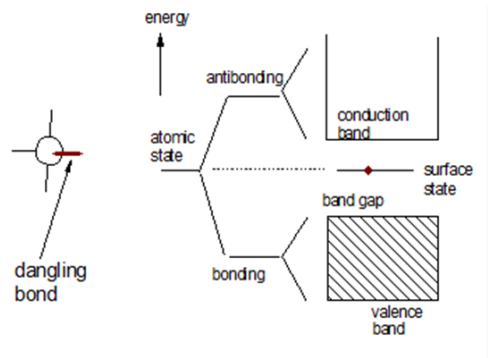
The opening part of this question was generally well-answered, but students were less clear about the requirements of CNT for specific engineering applications in part (d). Also, in part (c), an example of a dielectric 2D material was asked for, but most answers focused on graphene, which is a semiconductor, rather than a genuine dielectric material such as hBN.

a) Hybrid orbitals are linear combinations of atomic orbitals; these are s- and p- states for group IV elements and III-V compounds. Hybrid orbitals are not orbitals with lowest energy. The required energy for hybridisation is gained from the energetically favourable bonding configuration formed. Looking at the diamond phase of Carbon, there are only 2 electrons in the 3p orbitals. The full 3s orbital should not overlap with a neighbour and become involved in bonding. However, 3s and 3p energy levels are close, and it is energetically favourable for s and p orbitals to interact and form 4 sp3
hybrid orbitals. These sp3 orbitals overlap to form 4 bonds, resulting in tetragonal bonding geometry. It is the hybridized sp3 orbitals that form bonding and antibonding orbitals.



For bulk diamond, the bonding and anti-bonding levels broaden as electrons are not allowed same quantum numbers. Hence bands are formed.

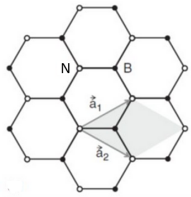
b) A free surface of Si consists of a series of broken bonds. These dangling bonds will produce gap states near middle of the gap (as not split into bonding/antibonding levels, see part (a)).



This is extremely undesirable. They cause recombination of carriers, and loss of conduction. To stop this happening, the surface state must be 'passivated'. For Si, this can be easily done by oxidation. This converts Si DBs in Si-O bonds, whose states lie outside the Si band gap, so they are inert. This is helped by the random, amorphous nature of the SiO_2 network. At the Si/SiO2 interface, the bonds of the Si can continue as Si-O bonds in the SiO2. Field effect transistors rely on high interface mobility, and it is the low defect density to its oxide that make Si so special. Thermal oxidation creates the SiO2:Si interface below the original Si surface. Any impurities which were originally on the Si surface, are now inside the SiO2, allowing an easy to manufacture device interface. Si is an average semiconductor, but it has the only good native oxide, hence its key role in the semiconductor industry.

c) Materials that adopt an intrinsically layered anisotropic crystal structure are referred to as 2D materials. They have no dangling bonds on their surface. Hence vertical heterostructures can be formed without stringent lattice matching constaints. Binding between layers is just by van-der Waals interactions, hence the term van-der-Waals heterostructures.

A suitable insulating layered 2D material is hexagonal boron nitride, h-BN. It is isostructural to graphene with slightly larger lattice constant. Its unit cell is composed of one boron atom and one nitrogen atom.



This means there is ionic (polar) bonding component, and unlike to graphene the B and N sites are different and this opens a large band gap (≈6eV) between π and π* bands.

d) For transparent electrode application, the CNTs needs to act as conducting channels, i.e. should be as highly conducting as possible. Metallic CNTs are thus preferred, or highly/degenerately doped CNTs. The films should be as transparent as possible, i.e. as thin as possible, so metallic single-walled nanotubes best suited. A SWNT is metallic when (n-m) is a multiple of 3. Armchair SWNTs are always metallic. Unlike indium tin oxide (ITO) films which are brittle, the use of SWNTs offers flexibility. Also the issue of In scarcity/mining is avoided.
For TFT channel applications, CNTs need to be semiconducting, ideally with a sizeable bandgap. Hence small diameter SWNT preferred (bandgap varies with 1/d). It is crucial to avoid having metallic SWNTs here, as they would act as short. Unlike amorphous Si or oxide channel films, CNT channels offer flexibility, transparency, and higher mobility.

e) For interconnect application it is important to keep RC constant low, hence a so-called low-K material is demanded to keep C low. There are not many materials with low dielectric constant. Example material are organo-silicon polymers SiCxHyOz. Recently also amorphous h-BN has been measured to have low dielectric constsnt.

Q4

Generally, well answered throughout except that many people did not pick up on the critical point that in organic semiconductors, screening is low and therefore it is more likely for excitons to form, which is critical to the optoelectronic application of these materials.

a) Direct bandgap of approx. 2.1 eV at K-point. Photon wavelength [nm] = 1240/2.1 = 590 nm
It is a direct bandgap because the lowest level of conduction band is aligned in k-space with highest point on valence band. No change in momentum is required for the transition.

b) In substitutional doping a dopant impurity atom replaces a Ga or N atom in the GaN lattice. For a III-V compound, we get p-type doping by substituting a group II element for III eg Mg at Ga site. There then is an absence of an electron. The hole forms a hydrogen-like series of acceptor states, just above the valence band edge.
The Rydberg constant R_0 (13.6 eV) is rescaled by the GaN values of ε_r and m* :

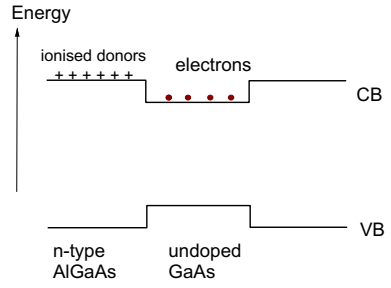
$$R = R_0 \, m^*/\varepsilon_r^2$$

and the binding energies are given by

$$E = -R \, 1/n^2$$

For the given case R is approx. 200 meV, which is much larger than KT at room temperature. Hence, the acceptor is not easily ionised.

c) Charge scattering by ionised impurities can be reduced by transfer doping. This relies on a heterostructure design.

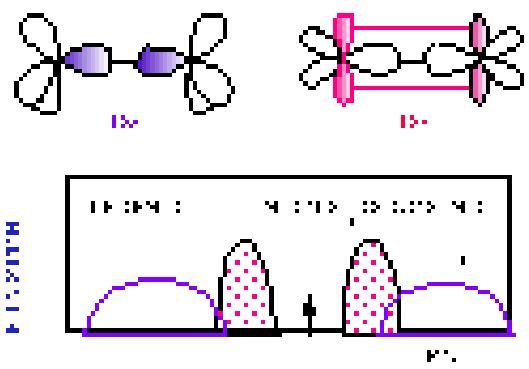


The donors are thereby in the wide gap region, but the electrons transfer to the narrower gap region, where they no longer get scattered by the ions. This gives the high mobility. In order to make such heterostructure, good epitaxy is required, ie the lattice contstants of materials used needs to be matched/similar. As there is correlation between lattice constant and the band gap, this means that such lattice fit is non-trivial. A much used exception is Al and Ga. AlAs is unusual in that Al is a bigger atom than Si, so that AlAs has the same lattice constant as GaAs. This is why GaAlAs is typically the material of choice for such heterostrutures (see so called Map of the World).

d) Amorphous semiconductors are not completely disordered. a-Si has the same bonding structure as crystalline Si (c-Si), except that it has a random network, not a periodic lattice. Following the 8-N rule, is such network P would not be forced to the Si bonding structure (ie would not be

substitutional) but be able to adopt to 3 bonds, ie would not act as dopant. The doping is quite inefficient compared to in crystalline Si.

e) Key to understand electrical transport in organic materials is the hybridization of carbon. In contrast highly directional 'σ-bonding', for sp2 hybridized carbon the remaining 2pz orbitals give rise to weaker π (bonding) or π* (anti-bonding) orbitals. The difference in these frontier orbitals is the organic equivalent of the semiconductor bandgap.



An exciton is a bound electron hole pair. Organic semiconductors are low dielectric constant (ε_r) materials. This means that screening is very low, and when for instance an electron is created by excitation from valence (HOMO) to conduction (LUMO) band, this creates a rather strongly bound (0.1-1 eV) electron hole pair.

f) Due to the monolayer nature of the WS2 screening is also low, and large (0.3 eV) exciton binding energies have been measured. Excitons are found to dominate the optical and charge-transport properties. Compared to (a), the (what is called) optical bandgap of WS2 would reduce according to binding energy of exciton, which can be seen in photoluminescence.