4C3 Crib

1) i) A pyroelectric element produces charge in response to a change in temperature. However for a small change in T this dissipates and is difficult, if not impossible, to measure. An incident modulated flux of heat energy gives rise to a ac current and voltage which can be amplified. $i_p = A p \frac{dT}{dt}$

ii) In this case the multiple Fresnel lenses create a large number of ones which are focussed onto the detector. A warm body moving through the detection zones creates, therefore a time modulated incident flux on the detector. $W(t) = W_0 e^{i\omega t}$ ω here depends on the rate at which the object cuts across the detection zones.

iii) There are two basic approaches. The current / voltage responsivity is proportional to ω. So if the intruder moves very slowly it is possible that the signal produced is below the detection threshold of the detector. The other approach would be to reduce the magnitude of the incident flux. Wearing low-emissivity clothing or insulation so the intruder was at the same T as the surroundings would also reduce the signal.

Finally you could shine a bright IR source at the detector and overload it. This might cause an initial detection though.

iv) A cold object is just as likely to trigger as a hot object as the detector is sensitive to $\frac{dT}{dt}$

b) i) $P_{IR} = \frac{V}{W_0}$ here $V = \frac{ip}{Y}$

Y ← amplifier's complex admittance

reciprocal of impedance

so $R_V = \dfrac{i_p}{Y W_0}$

ii) From $Y = \dfrac{1}{R_G} + i\omega C$ $(C = C_E + C_A)$

We also know that $G_T \tau_T = H$

Simple eqn expected to remember or derive

$\tau_E = \dfrac{C}{R_G}$

$$\left[i_p = A_p \frac{dT}{dt} \right] = A_p \left(i\omega \frac{\eta W_0 e^{i\omega t}}{G_T + i\omega H} \right)$$

(with $\dfrac{dT}{dt}$ indicated for the bracketed term)

so $R_V = \dfrac{i_p}{Y W_0} = \dfrac{A_p \eta e^{i\omega t} \, i\omega}{\left(\frac{1}{R_G} + i\omega C\right) G_T (1 + i\omega \tau_T)}$ from $\tau_T = \dfrac{H}{G_T}$

$C = \tau_E / R_L$

$$= \frac{R_G A_p \eta e^{i\omega t} i\omega}{(1 + i\omega \tau_E)(1 + i\omega \tau_T)}$$

$i\omega t$

$$R_v = \frac{R_G A_p \eta e^{i\omega t} i\omega (1+i\omega\tau_F)(1-i\omega\tau_T)}{G_T(1+\omega^2\tau_T^2)(1+\omega^2\tau_F^2)}$$

$$|R_v|^2 = R_v R_v^* = \frac{R_G^2 A_p^2 \eta^2 \omega^2 \cancel{(1+\omega^2\tau_G^2)}\cancel{(1+\omega^2\tau_F^2)}}{G_T^2(1+\omega^2\tau_T^2)^{\cancel{2}}(1+\omega^2\tau_F^2)^{\cancel{2}}}$$

so $$|R| = \frac{R_G A_p \eta \omega}{G_T\sqrt{1+\omega^2\tau_T^2}\sqrt{1+\omega^2\tau_G^2}}$$

iii) If ω is large

$$\frac{R_G A_p \eta \cancel{\omega}}{G_T \omega^{\cancel{2}} \tau_T \tau_G}$$

so at large ω $R_v \propto 1/f$

Q2 a) Monolayer NbS_2 is metallic, as Fermi level is mid-band, i.e. there is partially filled band. Question was seeking careful consideration, so if rightly argued (not taking $E_F = 0eV$) also full points awarded to semiconductor argumentation.

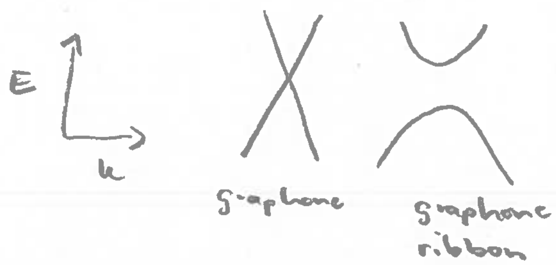
b) i)

Band dispersion is linear for graphene, and graphene is semi-metal or zero-gap semiconductor.

ii) The visibility of monolayer graphene on SiO_2/Si support comes from interference effects. The different colour for different twist angles of bilayer graphene is associated with enhanced absorption based on transitions to states that arise from different band overlaps (see figure).

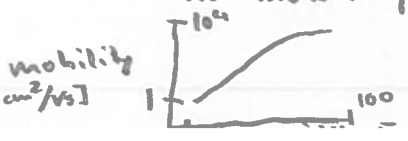
example of bilayer graphene band structure

iii) For ribbons with small enough width confinement effects will occur, alike to carbon nanotubes (CNTs). This results in the original 2D energy dispersion to split into 1D modes. If these 1D modes do not pass through intersection of conduction and valence band (K point), then those ribbons have finite gap.



Widths below 20 nm can give band gaps > 200 meV, for well controlled very small widths gaps > 1eV; a comparison again to CNTs here is helpful as order of magnitudes are similar.

The mobility will decrease with ribbon width, however, which is similar to conventional semiconductors.



Q2 c) i) Transparent conducting layer could be designed using graphene. The optical transmittance is ~ 2.3% per layer, and it will also be transparent in UV due to its thinness. High conductivity requires high mobility and high carrier concentration. So ideally highly crystalline graphene film and effective doping. Best solution to use few-layer graphene. Carbon nanotubes would offer similar design solution, but LED emitter integration will not be as easy (see ii).

ii) UV-C range is ~ 200-300 nm wavelength, so large band gap (> 4eV) emitter material is required for LED. A solution is AlGaN, as highlighted in the lectures by "Map of the world" material diagram. AlN and GaN have sim. lattice constant so heterostructure for efficient LED design can be fabricated. To relax epitaxy constraint, material stack can be grown as vertical nanowire. Graphene (see i) is 2D material, so epitaxial constraint is relaxed, and AlGaN material of sufficient quality can be grown directly on it. Alternatively, a transfer solution can be discussed for device assembly.

Q3 a) i) As is group V, so substitutional n-type doping of Ge will occur.

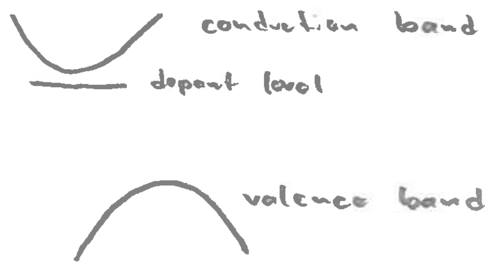
ii) hydrogenic model

$$E_{dopant} = -R_0 \frac{m^*}{\varepsilon_r^2}$$ for ground state below Ge conduction band

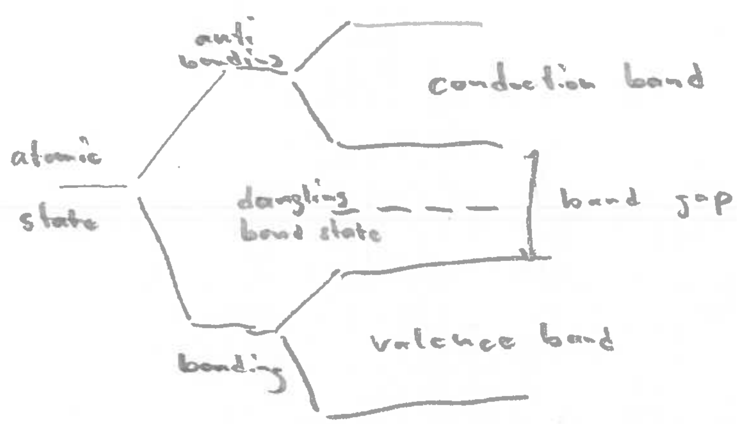
$$= -13.6\,eV \frac{0.55}{16^2} = 29\ meV$$

use effective mass for electrons as its n-type doping.

This is of order of kT at 300K, so dopant level will be ionised.



iii) vacancy will have dangling bond and, using covalent bonding / antibonding picture, this will lead to state in mid-gap:



Such defects act like a "free radical" and can act as trapping and recombination centre, ie are electronically detrimental.

iv) CMOS technology is based on MOSFET transistors where not only semiconductor but also good dielectric is required. Electronic properties of SiO_2 are good, it is stable and importantly SiO_2 formation passivates dangling bonds of Si at interface. So low interface defect density

Q3 a) iv) can be achieved. Ge does not have such a stable and useful native oxide. Hence Si became the dominating material.

b) Ge has indirect band gap of ~0.7 eV.
The Shockley - Queisser limit places maximum solar conversion efficiency around 33.7% for single p-n junction with a material of 1.4 eV.
This means Ge band gap is too small. Si is better but still indirect band gap. Higher efficiency possible with direct band gap material like GaAs or hybrid perovskite like $CH_3NH_3PbI_3$.

c) i) Band diagram shows linear dispersion around K-point, with conduction and valence band touching. So its analogous to graphene, and germanene is semi-metal or zero band gap semiconductor. So not good material for standard transistor, but it's 2D Dirac material with anomalous quantum effects with potential for novel optoelectronic devices.

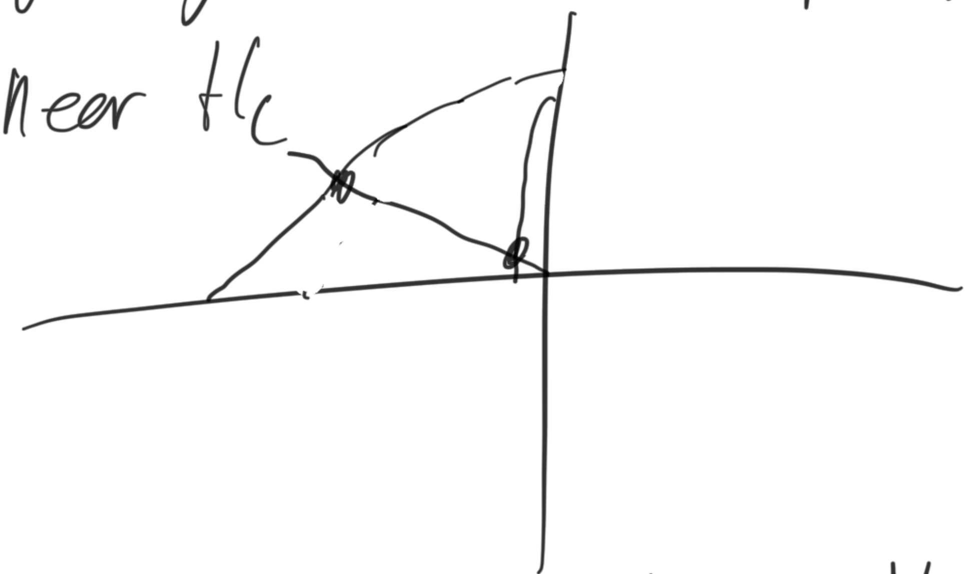
ii) Si and Ge are analogous here in this traditional semiconductor vs new 2D phase comparison. Silicine will also have linear dispersion and zero gap:

4C3 Crib

4 a) i) For $h = r$ $N \approx 1/2$

(students expected to recall)

Cobalt-Steel has a low (lowest) of all "permanent" magnet materials.
De-mag effect will cause spontaneous demagnetisation as operating point near H_c



SmCo has much larger H_c > 600 kAm^{-1} vs ~ -20 will stay magnetised even with $N = 1$!

ii) So

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

$$H = -MN \qquad M = -H/N$$

$$B = \mu_0 \left(-\frac{H}{N} + H \right)$$

$$B = H \mu_0 \left(1 - 1/N \right)$$

$$\frac{B}{H} = \mu_0 \left(1 - 1/N \right) = -\mu_0 \left(\frac{1 - N}{N} \right)$$

must be satisfied for a given N

iii) S… a… B–H characteristic

iii) So we have B-H relation

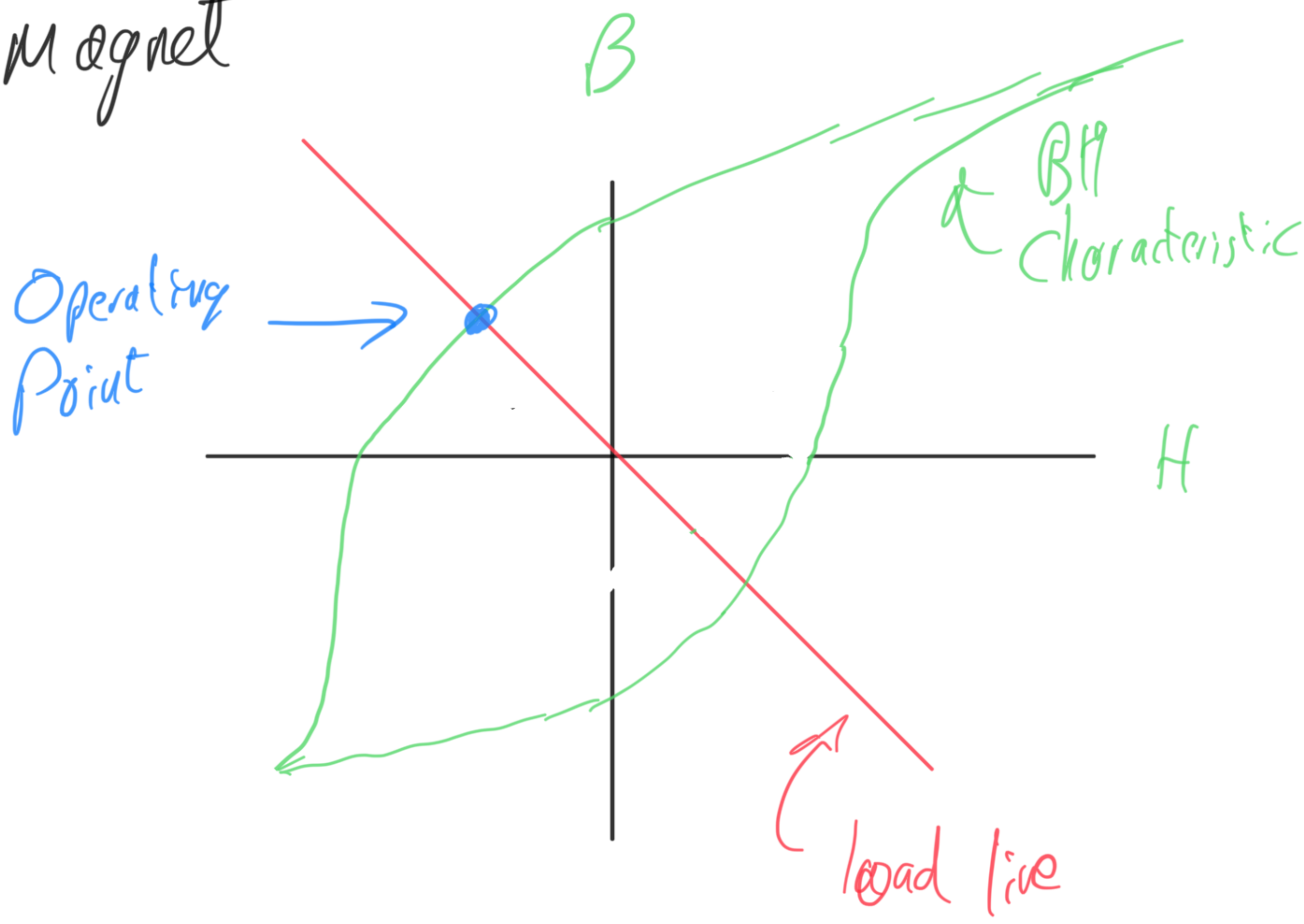
set by material's properties and

$\frac{B}{H} = -\mu_0\left(\frac{1-N}{N}\right)$ set by value of

N - the intersection of these

is the "operating" point of the

magnet



iv)

ii)

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

but $H = -MN$

$\propto$ to energy density in field actually $\frac{BH}{2}$

$$\frac{BH}{\mu_0} = -MN(M-MN)$$

$$= -M^2N(1-N)$$

So $BH = (M^2N^2 - M^2N)\mu_0 = \mu_0 M^2(N^2-N)$

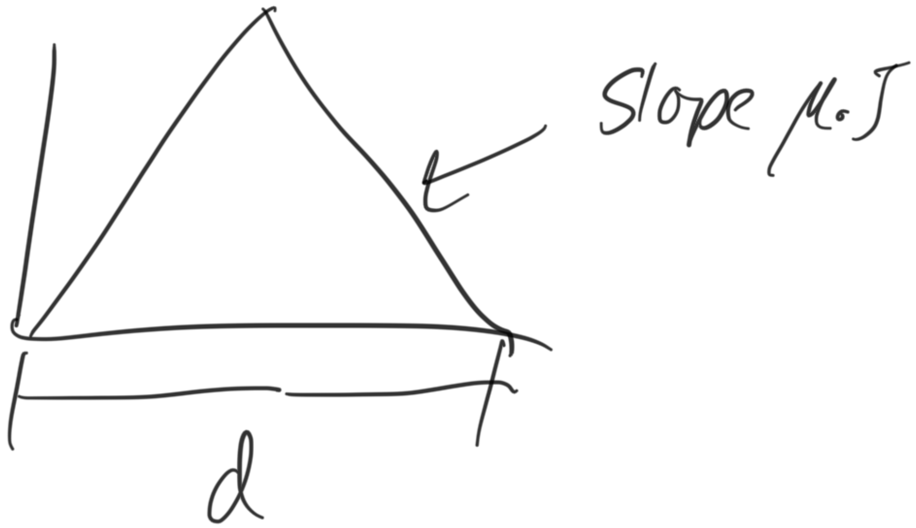
max when $\frac{d(BH)}{dN} = 0$

$$\frac{d(BH)}{dN} = \mu_0(2N-1) = 0$$

i.e. when $N = 1/2$

b) i) For superconductor field profile

is



Peak field is $\mu_0 J \frac{d}{2}$

$1.257 \times 10^{-6} \times 1 \times 10^{8} \times 3 \times 10^{-3}$

$= 0.3771$ T

but M is half this (as need to

integrate in this simple case/

so $\mu_0 M = 0.18855\ T$

$M = 1.5 \times 10^5\ A/m$

For NdFeB $N = 0$ so

operating point is $H = 0$ as $-MN = 0$

$B = \mu_0 M$ From data book

$B = \sim 1.32 T$

as magnet M is same everywhere

$M = \sim 1 \times 10^6\ A/m$

ii) So... if the critical current of a superconductor is not that high

Small pieces of superconductor would still be inferior to permanent magnet materials.

However as M α d for a superconductor this would not hold for larger samples

<u>Also</u> T_c is 30°C – very easy to demagnetise.