4C3 – (2017) CRIB

Q1 (a) for detailed description of deposition techniques, see lecture notes.

(i) Chemical vapour deposition (CVD): film is grown by decomposing gaseous silicon precursor on heated sample surface (decomposition rate can be enhanced by plasma, ie PECVD).

(ii) Thermal evaporation: relies on heating source material (here Au) high enough for vapour pressure to become significant and material to evaporate (or sublime from solid state) onto target substrate. Low vacuum pressure gives higher evaporation rate and clean conditions. (Sputtering also possible answer)

(iii) Atomic layer deposition (ALD): breaks the CVD process into two half reactions, each of the two surface reactions being self-limiting. Product film is formed in stepwise fashion, and atomic level thickness control possible via these cyclic exposures.

(b) HfO_2 film thickness can be measured by (spectroscopic) ellipsometry, where the change in light polarization is measured upon reflection from film/substrate interfaces (see lecture notes). The optical properties of the substrate/film have to be known to calculate thickness.

(c) Impingement flux of water molecules given by:

$$J_{H2O} = \frac{1}{4} n\bar{v} = \frac{p}{\sqrt{2\pi mkT}} = \frac{10^{-4}\, Pa}{\sqrt{2\pi 18u 298K}} = 3.6\times10^{18}\, molecules/m^2 s$$

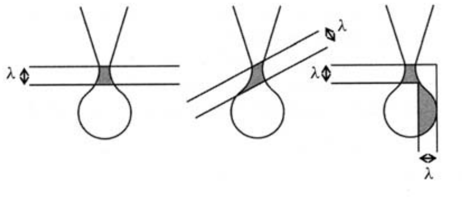
In comparison the arrival rate of Al atoms is:

$$J_{Al} = R_{evap} \times \frac{\rho_{Alfilm}}{m_{Al}} = 1.8\times10^{19}\, atoms/m^2 s$$

Hence ratio $J_{Al}/J_{H2O}=5$

(d) (i) The surface energy of Ni is higher than that of the SiO_2 substrate (see lecture notes on thermodynamic aspects of film nucleation), which is why Ni film dewets and splits into small islands.

(ii) Secondary electrons (SEs) are those electrons ejected out of bonds and bands in response to an inelastic interaction with the primary beam. SEs have kinetic energies less than 50 eV, and they can escape only from the very surface of the sample (mean free path, λ, only nm). Hence SE signal reflects sample surface, and SE emission dependent on sample topography:

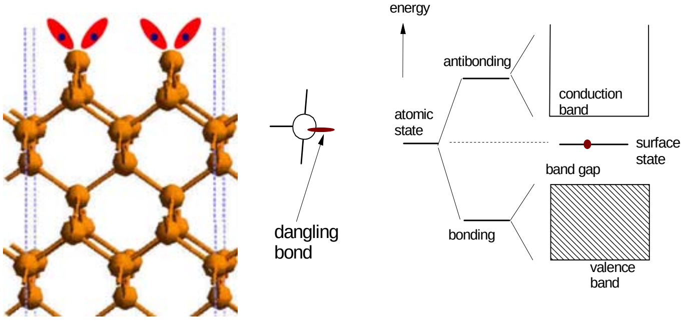


(iii) Backscattered electrons (BSE) are those primary beam electrons that escape the surface through

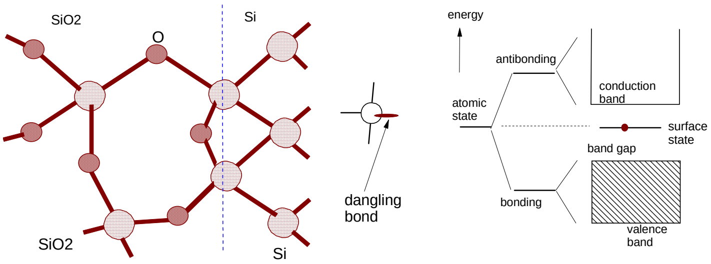
multiple electron-atom interactions (Rutherford scattering). They usually retain a large fraction of their original energy and their interaction profile with the sample is larger compared to that of SEs. This means that resolution can be expected to be lower compared to d(ii). The BSE yield (number of BSE/number of primary e-) increases monotonically with Z of specimen. So the contrast can be expected to increase, as Ni islands will appear brighter.

Q2

a)



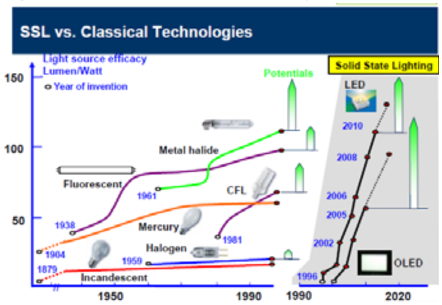
Surface states in band gap come from dangling bonds on the surface,



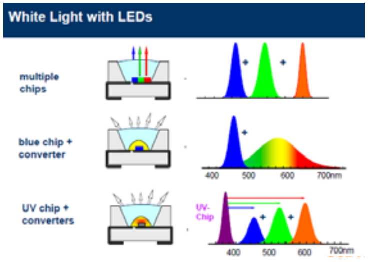
SiO2 makes Si-O bonds to all these dangling bonds, and in doing so, removes their states from the band gap.

(b) Solid State Lighting

Lighting is about 20% of total energy use. Incandescent lights are very inefficient. Fluorescent lighting is much more efficient. We now suffer from dim ‘compact fluorescents’. This is only a short term problem.But the ultimate light source will be GaN based white lights. These are already in use in car head lights.

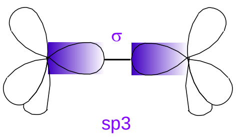


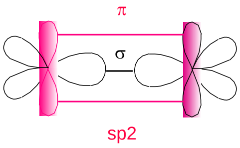
In principle, white light could be made in 3 ways; (1) using 3 different LEDs, (2) down-converting from a blue source, or (3) down converting from a UV source. (2) is the cheapest and does not expose you to UV – it is used.

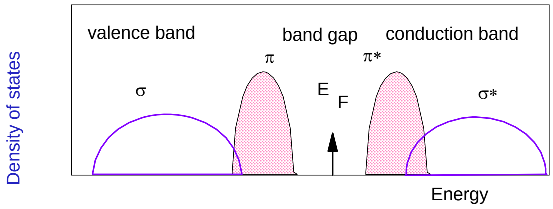


(c)

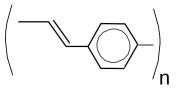
Sp2 vs sp3, and bond types. Pi bonds closest to band gap, determine conduction process for both electrons and holes.

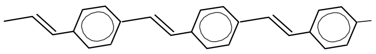






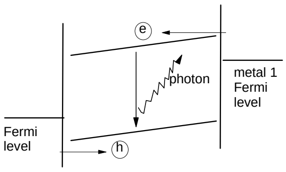
This shows the different types of bonds. The states next to the band gap are π states. Typical organic conductors are PPV, poly-phenylene vinylene. It is a polymer of the mononer





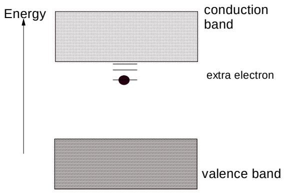
Need a continuous conducting path across the sample, so we need conjugated bonds.
Here, the double lines mean double bonds, that is one sigma bond plus one π bond. The hexagon is a benzene ring of 6 carbon atoms. Electrons can move relatively easily along the π bonds along the polymer chain. This is because each atom has a π state on it. Such molecules are called *conjugated*.

(d) No doping in organics. Electrons injected into CB states, holes injected into VB states, they move along and recombine in the middle, to create light.
Electrodes must have suitable work functions to inject over these barriers into the bands.



Q3

a) The P atom has a stronger potential than the Si atom it replaces, so that it still attracts this extra electron towards it, but only weakly.



Its potential is a 1/r potential just like that of the proton in the *hydrogen atom*. But it is not in free space, it is now screened by the dielectric constant of the Si.

Hence, the P atom gives rise to an energy spectrum of *donor states,* just like the levels of the hydrogen atom, referenced to the *conduction band edge* of Si*,* not the vacuum. The energies are scaled from the bare Bohr atom formula by the dielectric constant of Si, ε, and by the effective mass of the electron in Si, m*. Recall from Appendix that the binding energy of the electron in the hydrogen atom 1s state is

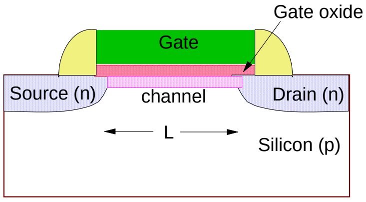
$$E = -R_0\frac{1}{n^2} \qquad \text{where } R_0 = \frac{e^4 m}{32\pi^2\varepsilon^2\hbar^2}$$

R_0 is the Rydberg or 13.6 eV. In Si, R is rescaled by the Si values of ε and m* (effective mass) $R=R_0 m^*/\varepsilon^2$.

(b) solubility limit, doping state to deep in the gap so will not ionize, or compensated by intrinsic defects.

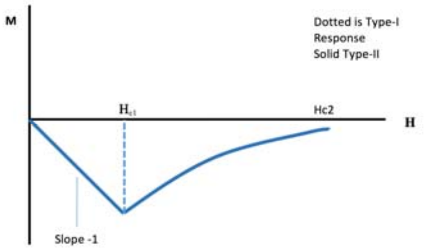
(c) $\sigma=n.e.\mu$. $\mu = e\tau/m^*$, hence small m* gives shallow dopants, easily ionised, and small m* gives large μ.

(d)



	1970	1990	2007	2016
Device	Planar FET	Planar FET	Planar	FinFET (>2015)
Channel	Si	Si	Strained Si	High mobility Ge, GaAs,
Gate	Al	Poly-Si	Metal	metal
Gate oxide	SiO2	SiO2	HfO2	High K HfO_2
Electrodes	Al	Al	NiSi	NiSi
Passivation oxide	SiO2	SiO2	SiCHO lo K	Low K
Interconnects	Al	Cu (2000)	Cu/W	Cu/W later CNTs?

Q4 a)i)

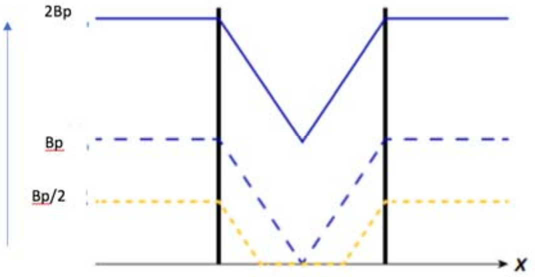


ii)
Type-I and Type-II superconductors differ in the sign of the free energy associated with the boundary between normal and superconducting materials within the material. This means that in Type-I materials, if geometric effects are discounted, the material will tend to try to exclude all magnetic field up to a critical field, H_c, at which the superconductivity is entirely suppressed. This accounts for a M-H curve that shows no magnetic response for large external fields and perfect diamagnetism for fields between $-H_c$ and H_c. It is worth commenting that H_c is often of the order of only a few mT.
In a Type-II superconductor the free energy associated with the N-S boundary means that above a small first critical field H_{c1} magnetic flux can penetrate into the superconductor in the form of flux vortices, each carrying one flux quantum Φ_0. As the external field is slowly increased more and more vortices penetrate which reduces the diamagnetism from 1 towards 0 at the upper critical field. In practical type-II materials pinning of flux vortices leads to hysteretic behaviour and a remanent magnetization (hysteretic version not required for full marks).

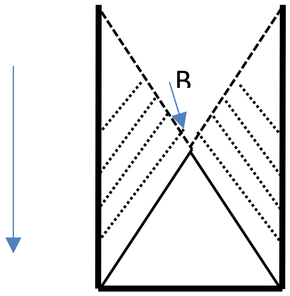
b) i) Slab is large so we can ignore geometric effects.
In 1-D the equation given simplifies to $d\mathbf{B}/dx=\mu_o \boldsymbol{J}+d\boldsymbol{D}/dt$. In a superconductor $d\mathbf{D}/dt$ is zero in DC field. The relationship between $\boldsymbol{B}$ and distance is therefore simply $d\boldsymbol{B}/dx= \mu_o \boldsymbol{J}_c$.

ii) The Bean model states that the only permissible values of J are 0 +Jc or –Jc. So the profile of field inside the slab, dB/dx can either be $+\ \mu_o \boldsymbol{J}_{c,}\ -\ \mu_o \boldsymbol{J}_c$ *or 0* .

To finish, with zero external field, with peak trapped field, B_p, the following sequence is required:



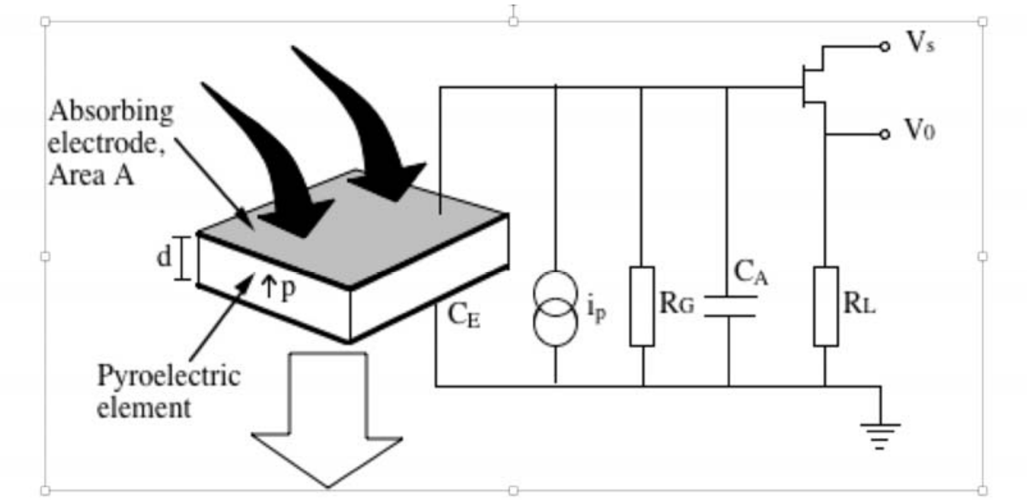
to get the peak trappable field, *Bp* in the centre of the slab. When the external field is removed field of opposite gradient is pushed in leading to the desired fully penetrated state.



iii) As there is no external applied field we can write that $\boldsymbol{M}=\boldsymbol{B}^{*}/\mu_o$ where $\mathbf{B}^{*}$ is the average magnetic field.

The maximum magnetisation for such a slab would be occur in the fully penetrated situation where the field rises to a peak at the centre of the slab. The peak **B**-field is thus given by $\boldsymbol{B}_{\boldsymbol{p}}=\mu_o \boldsymbol{J}_c d$ The average ***B***-field in the slab is half the peak field so $\boldsymbol{M}= \boldsymbol{J}_c d/2.$

Q5 Pyroelectricity



a) i)

The thermal time constant (τ_t) essentially depends on how quickly absorbed heat in the element is rejected to the environment. It depends, therefore, on the heat capacity of the element, H, and on the thermal conductivity of the element to its surroundings G_t.

$$\tau_t = H/G_t$$

(equation not required)

The electrical time constant, τ_e, depends on the capacitance of the element and the amplifier. It is a measure of how quickly charge is transferred from one to the other.

$$\tau_e = R_g(C_e + C_a)$$

(equation not required)

In current mode we are concerned about current generated by unit of input power. This is the case at low frequency of modulation of the input flux – say in a PIR detector.

In voltage mode we are concerned about voltage generated by unit of input power. This is the case at high modulation frequencies as might be expected in an imaging system where the input scene is deliberately chopped.

b) Separating out the materials parameters from the given equation to arrive at a figure of merit gives;

$$F_v = p/c\varepsilon_0\varepsilon_r$$

c) From given equations we can write:

$$\frac{R_V}{\Delta V_J} = \frac{p}{c\sqrt{\varepsilon_r \varepsilon_0 \tan\delta}} \times \sqrt{\frac{\eta}{4kTdA}} \times \sqrt{\frac{1}{\omega}}$$

and thus thinking about the materials parameters we can extract the following figure of merit.

$$F_d = \frac{p}{c\sqrt{\varepsilon_r \varepsilon_0 \tan\delta}}$$

d) The completed table is:

Material	**T_c** °C	**p** $\mu Cm^{-2}K^{-1}$	ε_r	**tan δ** $\times 10^{-3}$	**c** $MJm^{-3}K^{-1}$	**F_D** $\times 10^{-6}$/! Pa	**F_V** $m^2 °C^{-1}$
PVDF	80	27	12	15	2.6	9	0.1
$LiTaO_3$	665	230	47	0.1	3.2	351	0.17
SBN - 50	121	550	400	3	2.3	72	0.07
PZFNTU	230	380	290	10	2.5	58	0.06
PGO	178	110	40	0.5	2.0	131	0.16

$LiTaO_3$ is by far the best material. However, PVDF, in many ways the worst is a plastic. This means that it is much easier to create cheap large area detectors using PVDF . Indeed, PVDF is the basis of a number of practical infra red imaging systems because it is possible to make a large detector and then slice it up into a large number of pixels.

Q1 Very few people attempt this question, and nobody got part [c] right.

Q2 This was answered quite well. Most candidates could answer (a). Fewer could do (d).

Q3. This was an essay type question and was also answered quite well. Most candidates were able to list the new materials in CMOS and give some explanation for why they are used.

Q4 "On the whole this question was moderately well answered. In part b) many candidates confused the distinction between Type-I and Type-II superconductors to the distinction between a Type-II superconductor that was reversible and one that was not. In part c) many candidates lost marks by simply providing sketches from the notes without actually explaining the required process"

Q5 " This question was well answered. In part d candidates lost marks by providing rather cursory discussion of why PVDF is widely used in spite of having poor performance. In particular its polymer nature and consequent ease of processing was often overlooked"