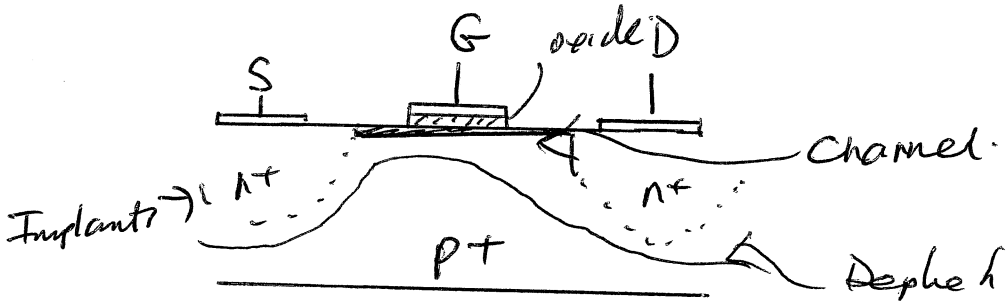
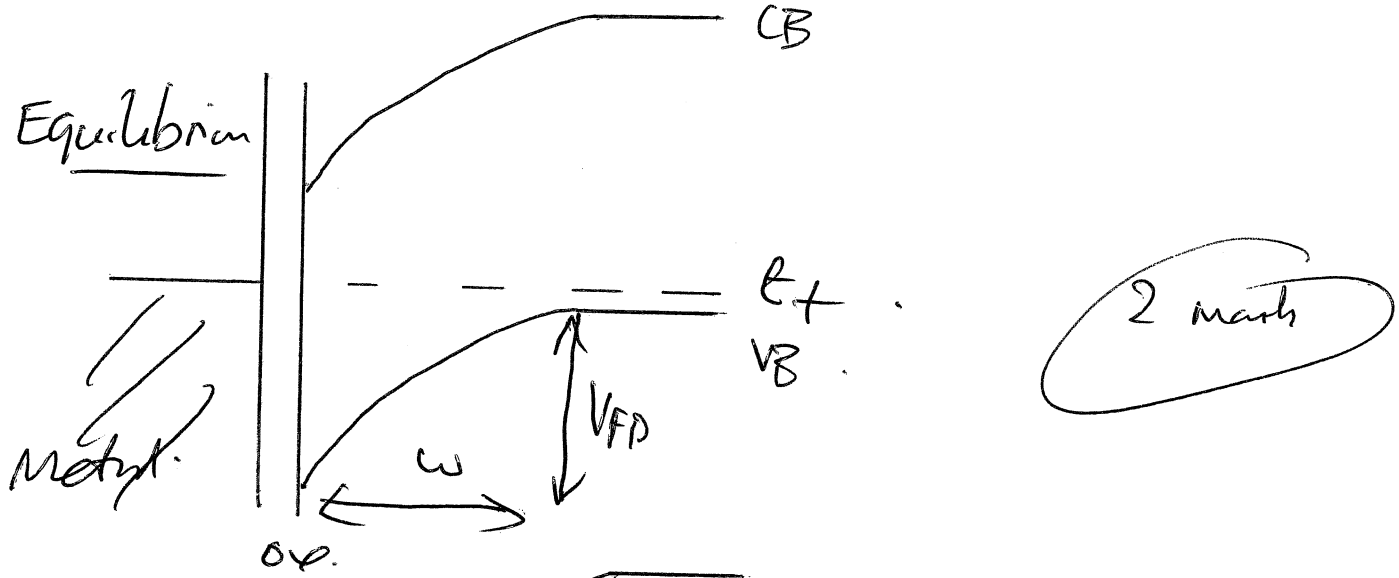
Solutions EEE6217 2014-15

1) a



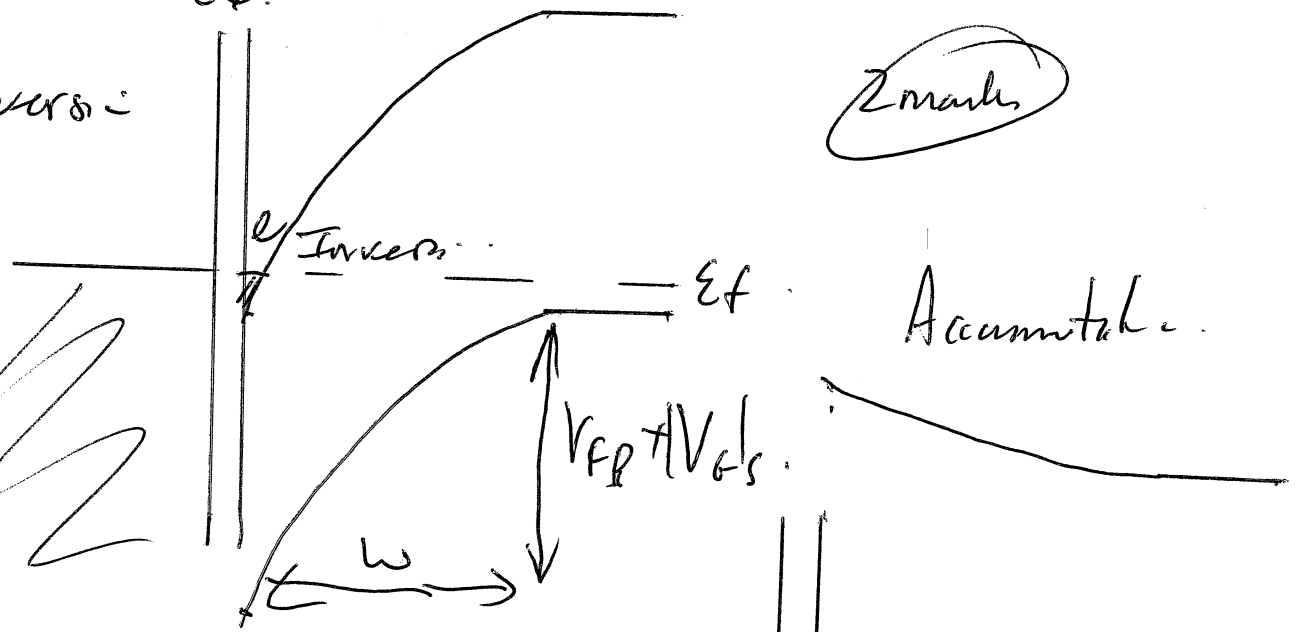
3 marks

b) Equilibrium



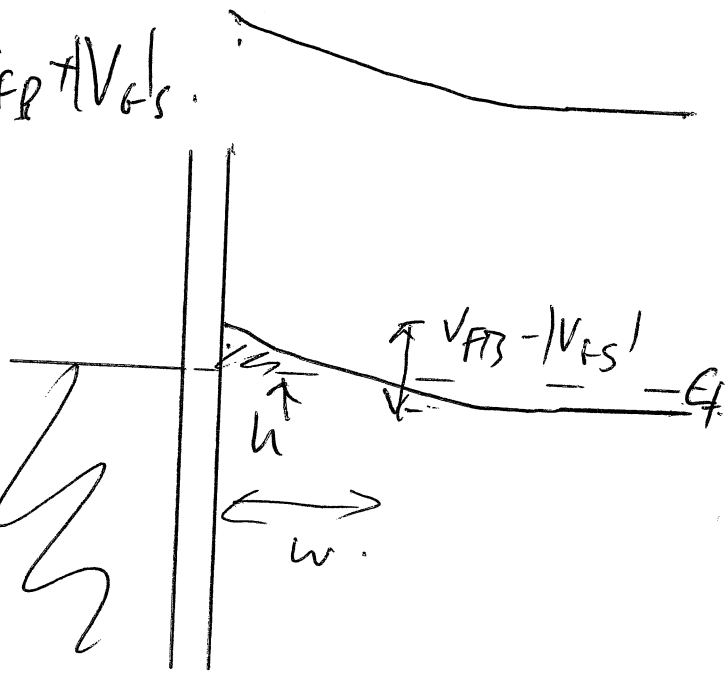
2 marks

Inversion



2 marks

Accumulation



2 marks

1b)

1c) $f = f_T$ when gain $\to 1$.

output current $= g_m V_{GS}$ input $= \omega C_{ox} 2L . V_{GS}$

↑ since this is Cap per unit gate area.

$$\frac{\text{output}}{\text{Input}} = \frac{g_m V_{GS}}{\omega C_{ox} 2 V_{GS}} = 1 \quad \omega = \frac{2\pi}{f}$$

$$g_m = \frac{2\mu C_{ox}}{L}(V_{GS} - V_T)$$ - from eqns at end of paper

$$f_T = \frac{g_m}{2\pi C_{ox} 2L} = \frac{2\mu C_{ox}}{2\pi C_{ox} 2L}(V_{GS} - V_T)$$

$$= \frac{\mu}{2\pi L^2}(V_{GS} - V_T)$$

2marks

Depends on mobility at $\frac{L}{L^2}$, so critically important is gate Length (L)

State of the art CMOS.

$\mu \Rightarrow$ Strained Si - using SiGe or tensile overlayer mobility increase through removal of degeneracy. pMOS - μ increased by factor of 2 $\Rightarrow$ nMOS - factor is smaller ~1.3-1.5

2marks

$L \Rightarrow$ Historical reduction in gate length - down to ~22nm in latest node.

Limitations $\to$ amount of strain in SiGe - dislocation (page 2) use higher mobility channel materials eg:

For L, the technological problem is to overcome the limits of optical lithography (EUV) or to switch to ebeam or to use self assembly.

Also device physics changes; ballistic transport quantum effects. (2 marks)

1d) $I_d = \frac{2\mu C_{ox}}{L}\left[(V_{GS}-V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$ from given equation

$I_D(2V) - I_D(1V) = 30\mu A = \Delta I_D$

$= \frac{2\mu C_{ox}}{L}\left[V_{GS}(2V) - V_{GS}(1V)\right] . V_{DS}$

since all other parameters cancel.

$= \frac{2\mu C_{ox}}{L}[1]\,0.1. = 30\times10^{-6}$

$\mu = \frac{\Delta I_D . L}{2C_{ox}[0.1]} = \frac{30\times10^{-6}\times 50\times10^{-6}}{200\times10^{-6}\times 1\times10^{-6}\times 0.1}$

$= \frac{30\times10^{-3}\times 50}{200\times 0.1} = \frac{1.5}{20} =$

$= 0.075\ m^2V^{-1}s^{-1}$

or $750\ cm^2V^{-1}s^{-1}$ (3 marks)

From data at end of paper
Bulk electron mobility of Si is $0.15\ m^2V^{-1}s^{-1}$

reduced by oxide scattering - surface channel is in proximity to Si/ox interface (2 marks)

2a. $r_{bb'}$ - base access resistance
contact and material resistance associated with the base

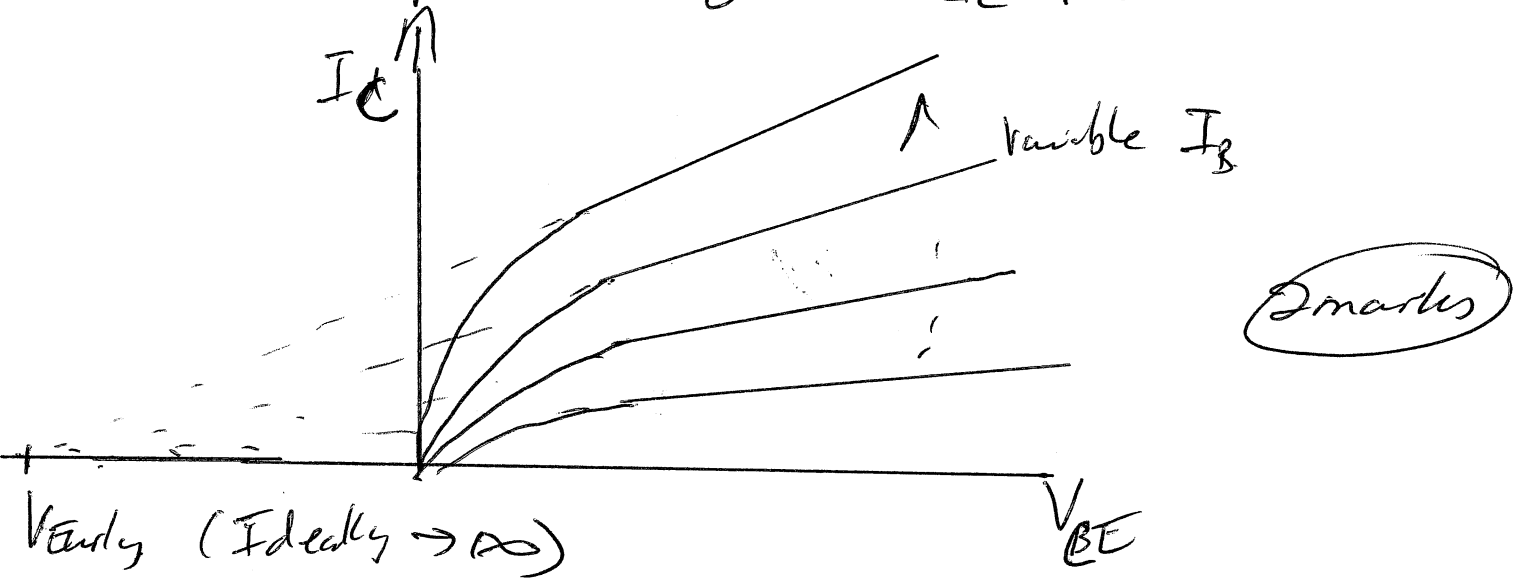
r_π dynamic input resistance $\left(\frac{dI_C}{dV_{BE}}\right)^{-1} = \frac{qI_e}{kT}$.

r_o dynamic output resistance $\left(\frac{dI_C}{dV_{CE}}\right)^{-1}$

$C_{b'e}$ - base emitter junction capacitance
Current source - controlled by $g_m V_{b'e}$.

(2 marks)

Increase in I_{BO} r_o is associated with the Early effect. High density of injected carriers saturates the BE depletion region → I_C falls.



(2 marks)

(i) Minimise $r_{bb'}$ - Increase base doping
(Limited in BJT → HBT overcomes this issue)

(ii) reduce r_o - reduce collector doping to allow depletion width to extend into the collector and not into the base

(page 4)

(iii) Increase r_π – increase the collector current

(iv) Reduce $C_{b'e}$ – smaller device area

(2 marks)

2b Input $i_b = i_{bo} + j\omega C_{b'e} V_{b'e}$

DC small signal

Output $= i_c$

$$\text{gain} = \frac{\text{output}}{\text{input}} = \frac{i_c}{i_{bo} + j\omega C_{b'e} V_{b'e}}$$

$$= \frac{1}{\frac{i_{bo}}{i_c} + \frac{j\omega C_{b'e} V_{b'e}}{i_c}}$$

β = DC current gain $= \frac{i_c}{i_{bo}}$

$i_c = g_m V_{b'e}$ (by definition)

$$= \frac{1}{\frac{1}{\beta} + \frac{j\omega C_{b'e}}{g_m}}$$

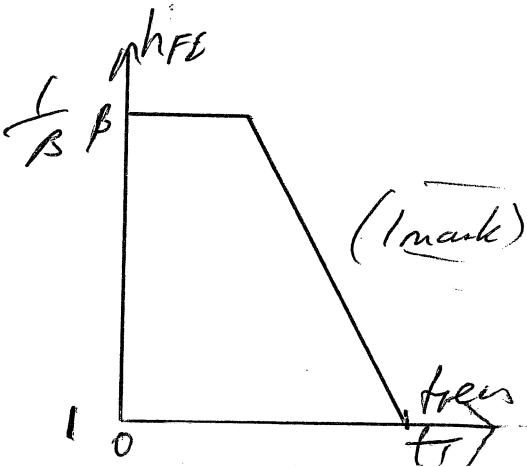
(2 marks)

At low frequency $\omega \to 0$ $\frac{1}{\beta} \gg$ 2nd term

$h_{fe} = \beta$ (1 mark)

At high frequency 2nd term $\gg \frac{1}{\beta}$

$$h_{fe} = \frac{g_m}{\omega C_{B'e}} \quad \text{(1 mark)}$$



(1 mark)

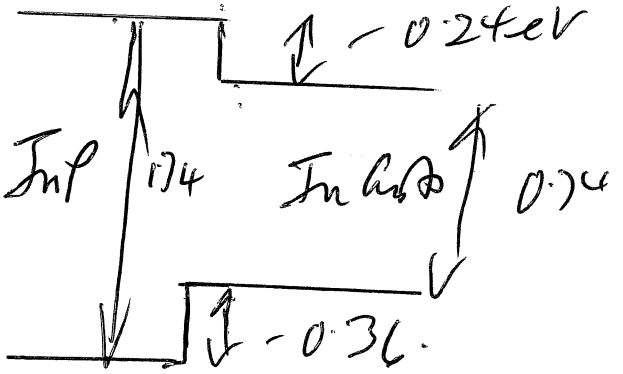
(page 5)

21) InP wide gap emitter (1 mark)

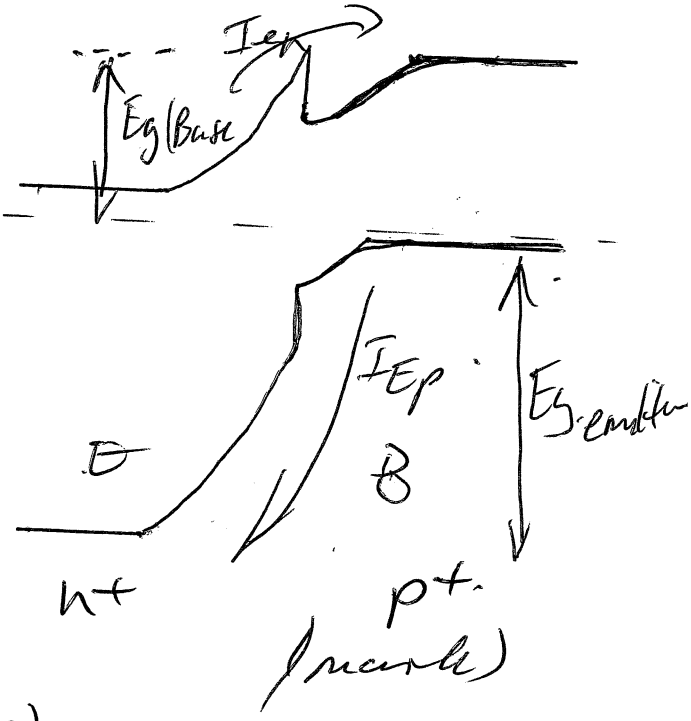
$\Delta E_g = 1.34 - 0.74 = 0.6\,eV$

$\Delta E_c = 0.4 \times 0.6 = 0.24\,eV$ (1 mark)

$\Delta E_v = 0.6 \times 0.6 = 0.36\,eV$



(1 mark)



(1 mark)

$$\frac{i_{en}}{i_{ep}} \propto \frac{N_E \exp^{-\frac{E_{g(base)}}{kT}}}{N_B \exp^{-\frac{E_{g(emitter)}}{kT}}}$$

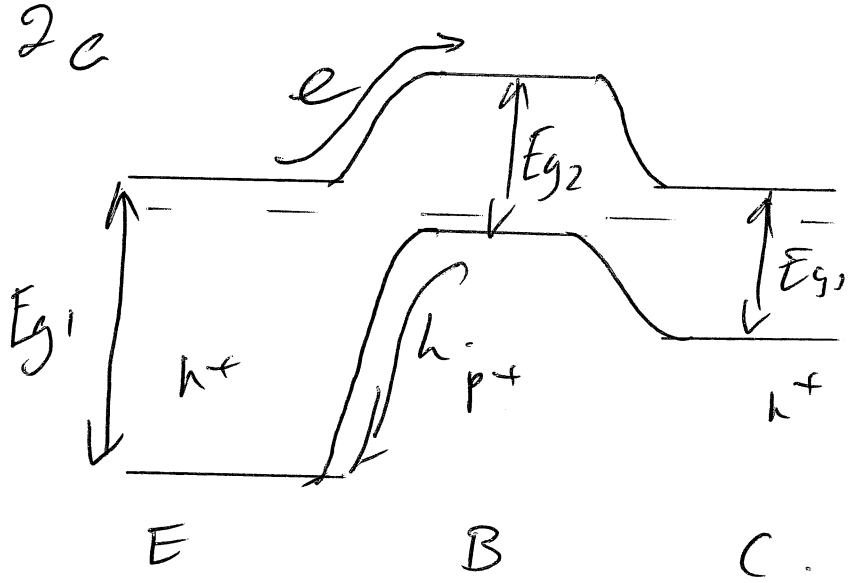
same ratio $\frac{N_B}{N_E} = \frac{e^{\frac{E_{g\,base)}}{kT}}}{e^{-\frac{E_{g(emitter)}}{kT}}} = \frac{e^{-\frac{0.74}{0.025}}}{e^{-\frac{1.34}{0.025}}}$

potential to increase the base doping by a huge factor. $= \frac{e^{-29.6}}{e^{-53.6}} = 2.6 \times 10^{10}$

(2 marks)

(page 6)

2c



$E_{g1} > E_{g2}$

(2 marks)

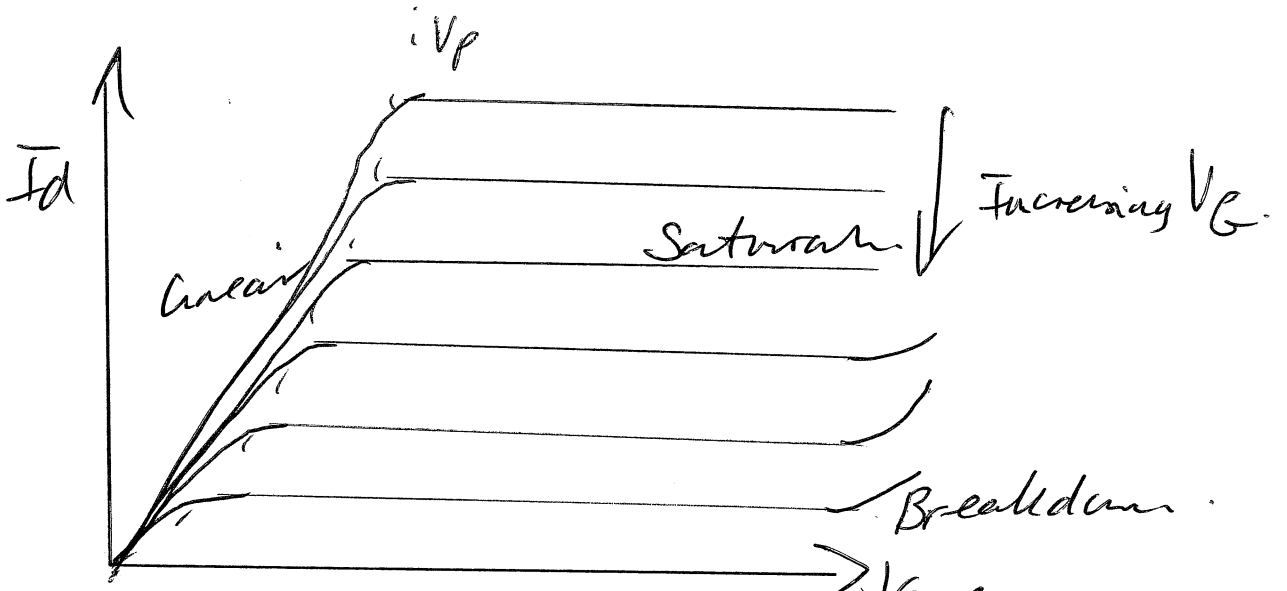
EB injection efficiency $\frac{i_e}{i_e + i_p}$ critical for a BJT.

increased barrier for holes reduces i_p, increases this. i_p limited in BJT by low base doping - HBT can allow high base doping which improves $r_{bb'}$

Use of narrow gap base materials, eg: SiGe, InGaAs generally increases their mobility.

(2 marks)

3a)

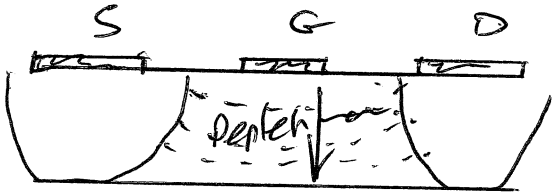


(2 marks)

Linear

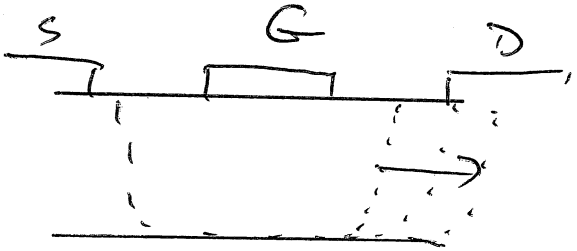
Width of the depletion region is extended linearly by the application of the gate voltage

Acts like a variable resistor on the source-drain current



(1 mark)

Saturation



Occurs after pinch-off

Depletion region extends almost to fully block the channel, but cannot completely close it - high field is preventing this

(1 mark)

(page 7)

Breakdown.

In the case of a high V_{GS} + V_{DS} a sufficiently high field can exist to induce avalanche breakdown. field must exceed the impact ionisation threshold. (1mark)

Drain current rises due to carrier multiplication

b) $$\text{Input} = I_{GS} = V_{gs}/Z = \frac{V_g}{C_G}\omega = 2\pi f C_G.$$ (1mark)

$$\text{Output} = I_{DS} = g_m V_G.$$ by definition of g_m (1mark)

$$\text{Gain} = \frac{O/P}{I/P} = 1 \text{ when } f \to f_T$$

$$\frac{g_m V_G}{2\pi f_T C_G V_G} = 1 \qquad f_T = \frac{g_m}{2\pi C_G}.$$ (1mark)

$$g_m = \frac{dI_D}{dV_G} \qquad I_D = n_s e V_{sat}.$$ - charge

$$g_m = \frac{d(n_s e) V_{sat}}{dV_G} = C_G/L \, V_{sat}.$$

So $$f_T = \frac{C_G}{L} V_{sat} \frac{1}{2\pi C_G} = \frac{V_{sat}}{2\pi L}.$$ (1mark)

$V_{sat} = 2\times10^7 \qquad L = 2\times10^{-7}$

$f_T = 1.59\times10^{10} = 15\,GHz$ (1mark)

(page 8)

3c

Pinch off $V_P = \frac{qa^2 N_D}{2\varepsilon_0 \varepsilon_r}$

$= \frac{1.6\times10^{-19} \times (0.5\times10^{-6})^2 \times 2\times10^{21}}{2 \times 8.85\times10^{-12} \times 12.9}$

$= 0.35\,V$ (1 mark)

Threshold $V_T = \phi_{bar} - V_h - V_p$.

$V_h = \frac{kT}{q} \ln\left(\frac{N_c}{N_D}\right)$ from additional data

$= 0.026 \ln\left(\frac{4\times10^{23}}{2\times10^{21}}\right)$

$= 0.14\,V$

$V_T = 0.8 - 0.14 - 0.35 = 0.31\,V$ (2 marks) (1 mark)

$I_D(sat) = \frac{2q}{\rho L} V_p \left[\frac{V_D}{V_p} + \frac{2}{3}\left(\frac{V_G}{V_p}\right)^{3/2} - \frac{2}{3}\right]$ equation given

At pinch off - need to know that $V_G + V_D = V_p$

substitute for V_D, or remember from lecture notes

$I_D(sat) = \frac{2q}{\rho L} V_p \left[\frac{1}{3} - \frac{V_G}{V_p} + \frac{2}{3}\left(\frac{V_G}{V_p}\right)^{3/2}\right]$

$V_G = 0.7\,V$ (page 9) $\left[\frac{1}{3} - \frac{0.7}{0.31} + \frac{2}{3}\left(\frac{0.7}{0.31}\right)^{3/2}\right] = 0.333$

$Z = 2.5 \times 10^{-6}$ $a = 0.5 \times 10^{-6}$

$\frac{2a}{\rho L} V_p$ $L = 1 \times 10^{-6}$ $\rho = 0.05\ \Omega.m$

$V_p = 0.31$

$= 7.75 \times 10^{-6}$

$I_{DSS} = 0.333 \times 7.75 = 2.58 \times 10^{-6} = \underline{2.6\mu A}$

(2 marks)

Transconductance

$g_m = \frac{dI_D(sat)}{dV_G}$ differentiate previous expression or remember from lectures

$-\frac{2a}{\rho L} \cdot \left[1 - \left(\frac{V_G}{V_p}\right)^{1/2}\right] = \frac{2a}{\rho L}\left[1 - \left(\frac{0.7}{0.31}\right)^{1/2}\right]$

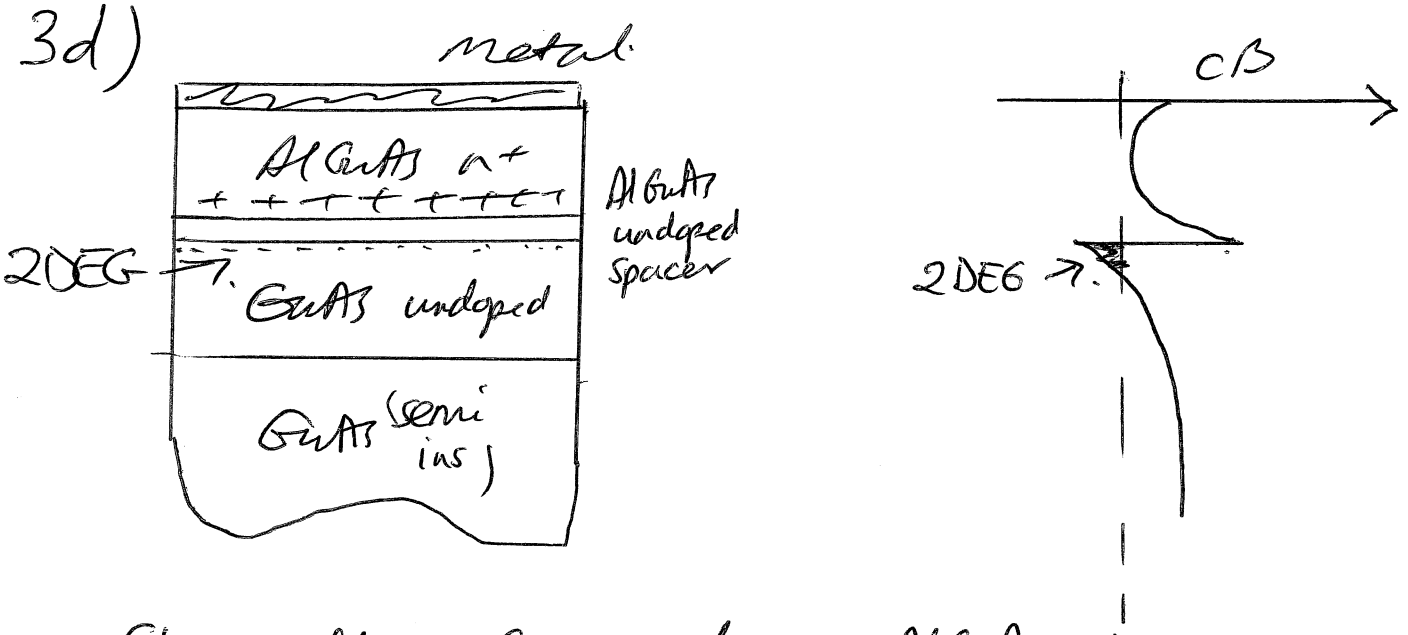
$\frac{2a}{\rho L} = 2 \times 10^{-5}$ $= \frac{2a}{\rho L}\left[1 - 0.503\right]$

$g_m = -1.258 \times 10^{-5}$ $12.6\mu A.V^{-1}$ $12.6\mu S$

Negative value - I_D reducing with V_{GS} as the channel closes.

(2 marks)

3d)



Charge flows from wide gap AlGaAs to narrow gap GaAs producing a thin channel of high density electrons at the interface - 2 D electron gas

(2 marks)

Advantages

(i) Separation of electrons from ionised impurities - increased mobility due to removal of ionised impurity scattering.

(ii) Channel precisely located + can be designed to be very close to the gate

(iii) Sheet charge fixed and relatively invariant on gate voltage or source-drain voltage

g_m and f_T improved due to mobility increase

g_m increased by proximity to gate

g_m more constant with V_G. (2 marks)

4a. Given V_{FB}

$$V_B = \frac{KT}{q} \ln \frac{N_A}{n_i} = 0.026 \times 15.42$$

$$= 0.401\ V. \quad (1\text{mark})$$

$$V_{ox} = \frac{\sqrt{2q\varepsilon_r\varepsilon_0 N_A |2V_B|}}{C_{ox}}.$$

$$2q\varepsilon_r\varepsilon_0 N_A |2V_B| = 2\times 1.6\times10^{-19}\times11.9\times8.85\times10^{-12} \times 5\times10^{22}\times2\times0.401.$$

$$= 1.351\times10^{-6}$$

$$V_{ox} = \sqrt{\frac{1.351\times10^{-6}}{18\times10^{-6}}} = 0.273\ V$$

(1mark)

$$V_T = -0.6 + 2\times0.401 + 0.273V = 0.493V$$

Reduction by factor $K = \left(\frac{45}{28}\right)$ (1mark)

All dimensions $\rightarrow \frac{1}{K}x$.

$$C_{ox} = \frac{\varepsilon_r\varepsilon_0}{d}$$ per unit area

$C_{ox} \rightarrow C_{ox} K$.

(1mark)

Depletion width - all dimension must scale with $\frac{1}{K}$. (1mark)

(page 12)

Depletion width $W \rightarrow \frac{W}{K}$ $\quad K = \frac{45}{28} = 1.607$

$$W = \sqrt{\frac{\varepsilon_r \varepsilon_0}{2N_A} 2V_B}$$

V_B - all voltages scale with dimensions

$V_B \rightarrow \frac{V_B}{K}$ (1 mark)

Scaled $\frac{W}{K}$ $\sqrt{\frac{\varepsilon_r \varepsilon_0 \; 2V_B/K}{2N_A(K)}}$

$N_A \rightarrow N_A K$.

N_A increases. (1 mark)

All voltages should scale except V_{FB}.

$$V_T = -|V_{FB}| + 2|V_B| + V_{ov}.$$

$$-0.6 + 2\,\frac{0.401}{1.607} + \frac{0.273}{1.607}$$

$$0.496 + 0.180 = 0.069V$$

(1 mark)

Short channel effect becoming worse at 28 nm device.

Depletion close to the drain has a greater effect on short devices.

1 mark

4b C_{ox} per Area $= \frac{\varepsilon_0 \varepsilon_r}{d}$ $\quad d_{28nm} = 1.56nm$.

$C_{ox} \rightarrow C_{ox} K = 1.607 \times 8 \times 10^{-6} Fm^{-2}$

$= 1.28 \times 10^{-5} Fm^{-2}$ (1mark)

$$\frac{I_{L_{28nm}}}{I_{L_{45nm}}} \frac{\sqrt{(\quad)}}{\sqrt{(\quad)}} \frac{e^{-K\phi_b^{3/2}/E_{28nm}}}{e^{-K\phi^{3/2}/E_{45nm}}}$$ (1mark)

$E_{28nm} = \frac{0.5}{1.56 \times 10^{-9}} = 3.21 \times 10^8 \ V.m^{-1}$

$E_{45nm} = \frac{0.5}{2.5 \times 10^{-9}} = 2 \times 10^8 \ Vm^{-1}$

$\phi_b = \psi_{Si} - \psi_{SiO_2} = 3.15 eV$ (1mark)

$K\phi_b^{3/2} = 2 \ 1 \times 10^8 \times 3.15^{3/2} = 5.59 \times 10^8$

$$\frac{e^{-5.59 \times 10^8 / 3.21 \times 10^8}}{e^{-5.59 \times 10^8 / 2 \times 10^8}} \quad \frac{0.175}{0.0611} = 2.86$$ (1mark)

$2.86 \times 0.7 = 2.00nA$.

(14) Significant increase in gate leakage can give rise to large static power dissipation. (1mark)

maintain capacitance

$$\frac{\varepsilon_{r,HfO_2}}{\varepsilon_{r,SiO_2}} = \frac{25}{3.9} = \frac{d_{SiO_2\,HfO_2}}{d_{HfO_2,SiO_2}}$$

$$d_{HfO_2} = d_{SiO_2} \times \frac{25}{3.9} = 1.56 \times 6.41 = 10nm.$$

(1 mark)

E field reduces $\frac{0.5}{10\times10^{-9}} = 5\times10^{7} Vm^{-1}$

but ϕ_b is lower $\phi_{Si} - \phi_{HfO_2} = 2.2eV$.

$m_{eff} = 0.55$ SiO_2 $= 0.11$ HfO_2

$$\frac{I_{HfO_2}}{I_{SiO_2}} = \frac{\sqrt{m_{eff,ox}}}{\varepsilon_{r,ox}\cdot\phi_b} e^{-K\phi_b^{3/2}/E} \Big/ \frac{\sqrt{m_{eff,ox}}}{\varepsilon_{r,ox}\,\phi_b} e^{-K\phi_B^{3/2}/E}$$

$$= \frac{0.0603}{0.0603}$$

Cancels out - so removed this

$$\frac{I_{L\,HfO_2}}{I_{L\,SiO_2}} = \frac{e^{-k\phi_b^{3/2}/E_{HfO_2}}}{e^{-k\phi_b^{3/2}/E_{SiO_2}}} = \frac{e^{-6.526}}{e^{-1.742}}$$

$$= 8.360 \times 10^{-3}$$

$$= \times 2\,nA = 16\,pA \qquad (2\ marks.)$$

c V_T determines the switching voltage V_{DD}

V_{DD} must be $\geq 2 \times V_T$ to allow adequate voltage swing. $P_{dynamic} \propto V_{dd}^2$. 1(mark)

Ultimate limit - Thermodynamic limit on.

but error rate $E_{Switch} = 3 K_B T$.

$= 0.078\,eV$ at 300K.

(1 mark)

Sub threshold - weak inversion regime.

Lowered dynamic power dissipation

logic delay times substantially increased.

(1 mark)

5a. (i) Drift Vel. $V_{Drift} = \mu E$

electrons $= 0.85 \times 5 \times 10^5 = 4.2 \times 10^5$ m.s^{-1}

holes $= 0.04 \times 5 \times 10^5 = 2 \times 10^4$ m.s^{-1}

(1 Mark)

(ii) $V_{Th} = \sqrt{\frac{2K_B T}{m}} = \sqrt{\frac{2 \times 1.38 \times 10^{-23} \times 300}{m^* \times 9.1 \times 10^{-31}}}$ (1 Mark)

electrons $= \sqrt{1.34 \times 10^{11}} = 3.66 \times 10^5$ m.sec^{-1}

holes $= \sqrt{2.02 \times 10^{10}} = 1.42 \times 10^5$ m.sec^{-1}

(iii) $V_{ar} = \sqrt{(V_{drift})^2 + (V_{Th})^2}$

electrons $= 5.57 \times 10^5$ m.s^{-1}

holes 1.43×10^5 m s^{-1}

(1 mark)

(iv) $\tau_{mfp} = \frac{m\mu}{q} \Rightarrow$ electrons $= \frac{0.85 \times 0.068 \times 9.1 \times 10^{-31}}{1.6 \times 10^{-19}}$

$= 3.3 \times 10^{-13}$ sec

holes $= 1.02 \times 10^{-13}$

$L_{mfp} = V_{ar} \times \tau_{mfp}$ = electrons $3.3 \times 10^{-13} \times 5.57 \times 10^5$

$= 1.28 \times 10^{-7}$

$= 128$nm.

holes $1.43 \times 10^5 \times 1.02 \times 10^{-13}$

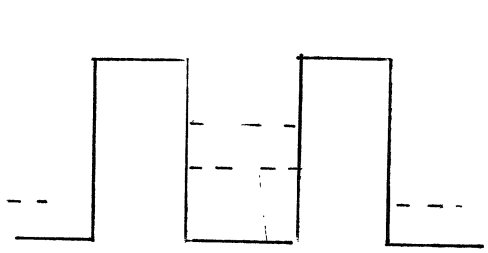
$= 14$nm

(1 mark)

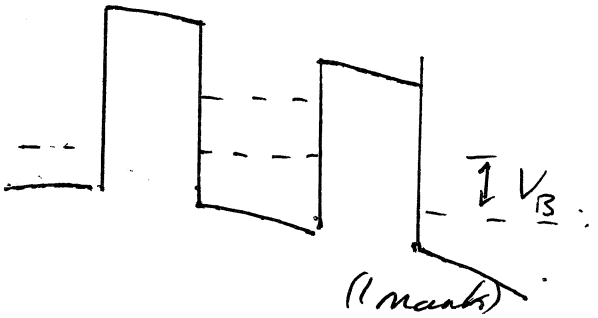
$d < 128$nm Enter ballistic transport regime - No scattering events. Conductivity becomes quantised in multiples of $\frac{e^2}{\pi h}$

(17)

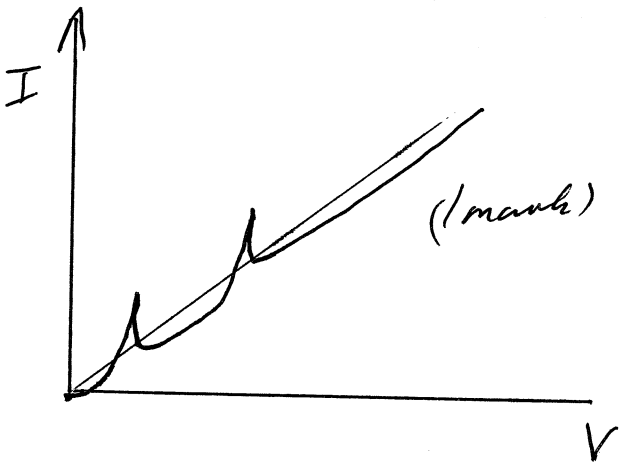
5b.



(1 mark)



(1 mark)



(1 mark)

$$E_n = \frac{\hbar^2}{2m}\left(\frac{\pi n}{a}\right)^2 \times \frac{1}{q} \text{ in eV}$$

$n=1$ $= 0.22\text{eV}$

0.055eV

$n=2$ 0.222eV

(1 mark)

RTD – large changes in drain current for small voltage change

Very fast switching – sub ps tunneling process

Very high conductivity on resonance

possibility to have multiple logic states (1 mark)

5c. $I_{EC} = I_{BE} + I_{BC} + I_B + I_C$

$$= \frac{kT}{q} C_{BE} \frac{I_E}{} + C_{BC}\left(\frac{kT}{qI_C} + r_E + r_C\right)$$

$$+ \frac{W_B^2}{2D_e} + \frac{W_C}{2V_{sat}}$$

(18)

$I_E \simeq I_C$

Simplify

$$\frac{kT}{qI_C}(C_{BE}+C_{BC}) + (r_E + r_C)C_{BC} + \frac{W_B^2}{2D_e} + \frac{W_C}{2v_{sat}}$$

$\frac{W_B^2}{2D_e} = \frac{(2\times10^{-7})^2}{2\times3.9\times10^{-3}} = 5ps.$

$r_E = 0.1\Omega$

$r_C = 0.2\Omega.$ (1 mark)

$\frac{W_C}{2v_{sat}} = \frac{1\times10^{-6}}{2\times1\times10^{5}} = 5ps.$

$C_{BC}(r_E + r_C) = 0.6ps.$

Total others (1 mark)

$= 5+5+0.6 =$

$10.6ps$

~~$\frac{kT}{qC_{BE}} = 0.026$~~

$\frac{kT}{q}(C_{BE}+C_{BC}) = 0.026\times5\times10^{-12}$

$= 1.3\times10^{-13}$ (1 mark)

$0.1mA \rightarrow 650ps + 10.6 = 660.6ps$

$2mA \rightarrow 65ps + 10.6 = 76.6ps$

$20mA \rightarrow 6.5ps + 10.6 = 17.1ps$

$f_T = \frac{1}{2\pi\tau_{EC}} = 2.4\times10^{9}, 2.07\times10^{9}, 9.3\times10^{9}$

~~2406~~ 0.24GHz, 2.07GHz (2 marks)

9.3GHz

Need small capacitance

- Small device area (1 mark)

(1a) Reduced resistances $R_E + R_C$ High doping

thin base & collector

5d.

Materials

III-V MOS, high mobility III-V's, graphene

(2marks)

Structures

Nanowires, nanotubes, single electron transistor.

(2marks)

6.

Gate Length

Reduced gate length increases g_m, I_D & f_T

reduces V_T, power dissip. Explain

provides higher device density.

physical limits - oxide tunneling, ballistic transport

short channel effect (DIBL). Explain.

Technological limit : optical lithography.

(2marks)

Strained Silicon

Used SiGe to compressively strain Si channel.

lifts VB degeneracy, pushing lower effective mass band up. Explain

Improves poor hole mobility - improves g_m & f_T

Limits - Strain relaxed - dislocations - low μ.

Technological limit - dependent on lithography

(2marks)

Oxide K

Gate oxide tunneling is significant in thin SiO_2

Maintain capacitance by increasing L_e and increasing thickness

(20)

(d)

HfO_2 ε = 5× higher than SiO_2

5m same capacitance, larger thickness, lower leakage

Limits: Scaling has now reduced the thickness of ~~Si~~ HfO_2 to the extent that oxide tunneling is now an issue again.

Techology - seek higher k oxides — perovskytes
interface problems reducing barrier height.

(2marks)

Low k interconnect

Interconnet delay

$$T = R_{tr}((C + C_l) + r_l((C_G + C_l)$$

need to reduce capacitance of interconnects

need low k - fluorosilicate glass (FSG)
thin diamond-like films.

reduce resistance - copper - damascene.

(4marks)

Multiple 3-d gates

- ~~Spreads the fi~~. Reduces spread of field

and acts on channel from 3-sides

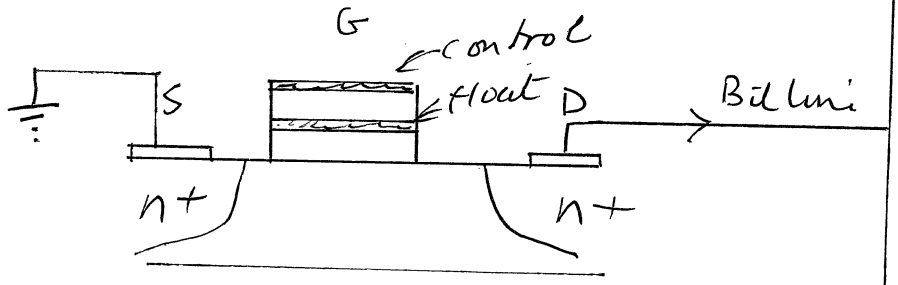
More effective gate action at low voltage
- higher g_m, - leads to lower V_T: - V_{dd}

At the limits of optical lithography.

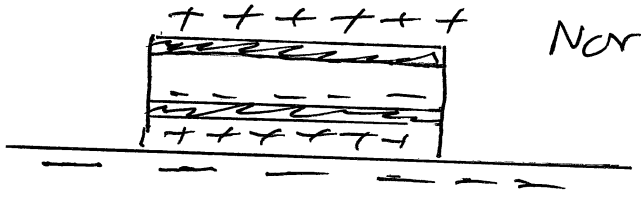
(4marks)

(21)
(e)

6b



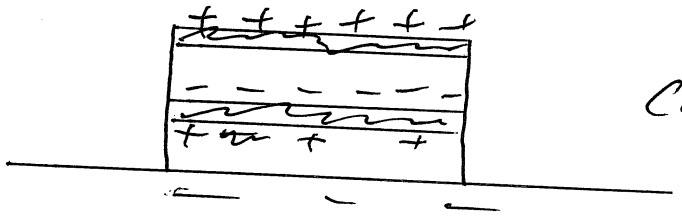
Device has a floating gate separated from the control gate by another oxide layer. Charge state of floating gate can be changed by applying a large voltage pulse to encourage tunneling.



Normal FET operation
- no net charge on floating gate (just polarisation charge)

V_T - low.

(2 marks)



Charge on floating gate reduces accumulation of electrons in channel.

V_T - increase.

Device read by applying a gate voltage above the lower value of V_T

Will turn on Source-Drain and drag bit line down to ground if no charge on gate (zero bit)

No change if charge is on floating gate (1 Bit).

(22)

Erase - Apply large +ve gate pulse
Bends the bands sufficiently to allow electrons to tunnel out of the floating gate

(2marks)

Read voltage $= 1.2V$ $V_T = 0.7$

will need to change V_T to $\geq 1.2V$ when charge present on floating gate

$\Delta V_T = 0.5V$ $\Delta V_T = \frac{\Delta Q_{float}}{C_{ox}}$ $\Delta Q_{float} = C_{ox} \Delta V_T$

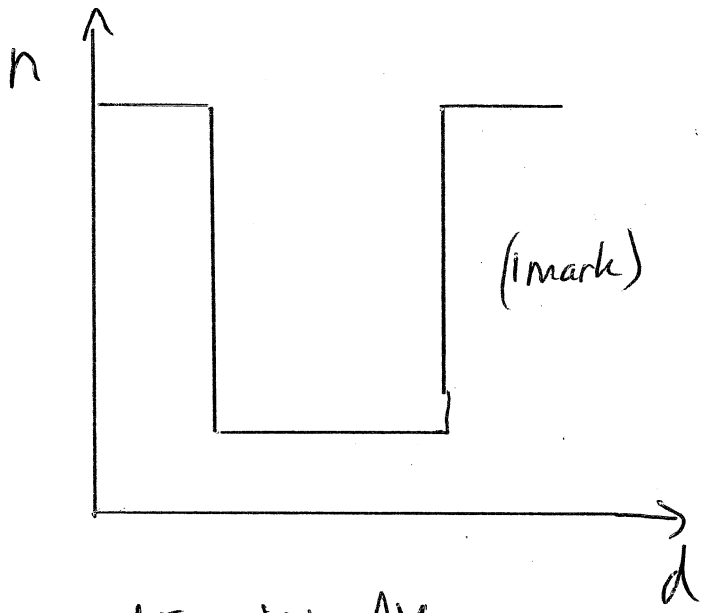
$\Delta n_{float} = \frac{C_{ox} \Delta V_T}{q}$ $C_{ox} = \frac{3.9 \times 8.85 \times 10^{-12} \times 45 \times 10^{-8}}{4 \times 10^{-9}}$

$= 5.44 \times 10^{-17} F$

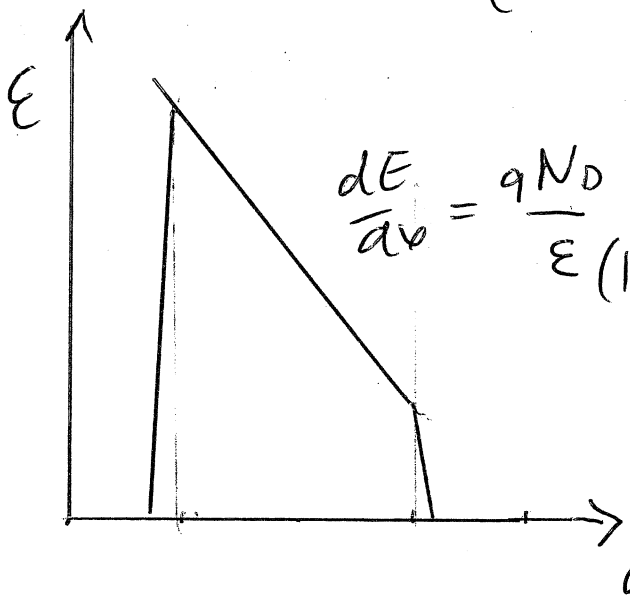
$= \frac{5.44 \times 10^{-17} \times 0.5}{1.6 \times 10^{-19}}$ $= 170$ electrons

(2marks)

6c



(1mark)



$\frac{dE}{dx} = \frac{qN_D}{\varepsilon}$ (1mark)

$\Delta E = \frac{\Delta N q \Delta x}{\varepsilon}$ =

(23)

$$\tau = \frac{d}{v_{sat}} = \frac{2\times10^{-6}}{10^5} = 2\times10^{-11}$$

$$f = \frac{1}{2\tau} = 5\times10^{10}\ Hz = 50\ GHz \quad (1\ mark)$$

Breakdown $\alpha L \to 1 \quad M \to \infty$

$$\alpha = \frac{1}{L} \qquad \alpha(E) = \beta(E) = A e^{-\frac{\beta}{E_{TH}}} = \frac{1}{L}$$

$$\frac{1}{LA} = e^{-\frac{\beta}{E_{TH}}} \qquad \ln\left(\frac{1}{LA}\right) = \frac{-\beta}{E_{TH}}$$

$$E_{TH} = \frac{-\beta}{\ln\frac{1}{LA}} = \frac{\beta}{\ln\frac{1}{1\times10^{-6}\times3.8\times10^{-7}}}$$

$$E_{TH} \frac{=\beta}{-3.638} = 8.2\times10^7\ V.m^{-1}$$

$$E.\Delta x = 82.5\ V \qquad (1\ mark)$$

APD - device held just below (at or) breakdown.

Incoming photons generate electron-hole pairs which increases current in the avalanche region leading to multiplication -

(1 mark)