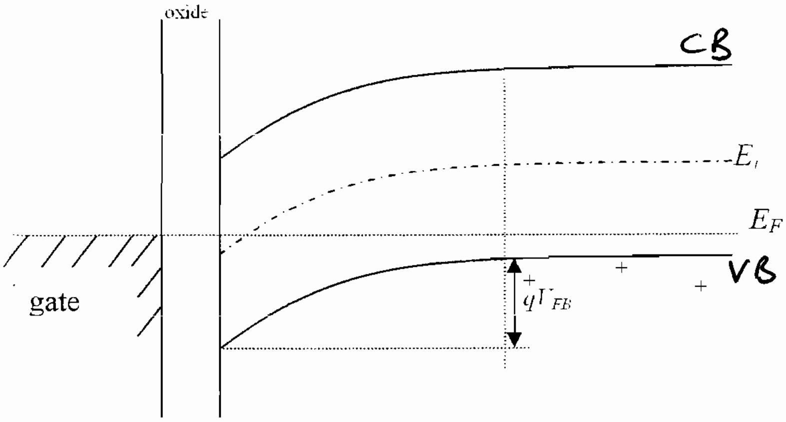
EEE 416/6040   08/09

High Speed Electronic Devices

Solutions

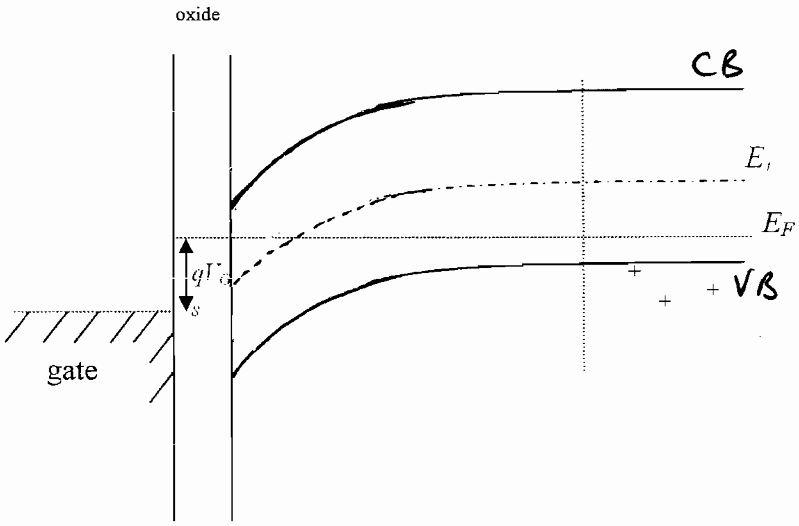
①

Q1 (a)



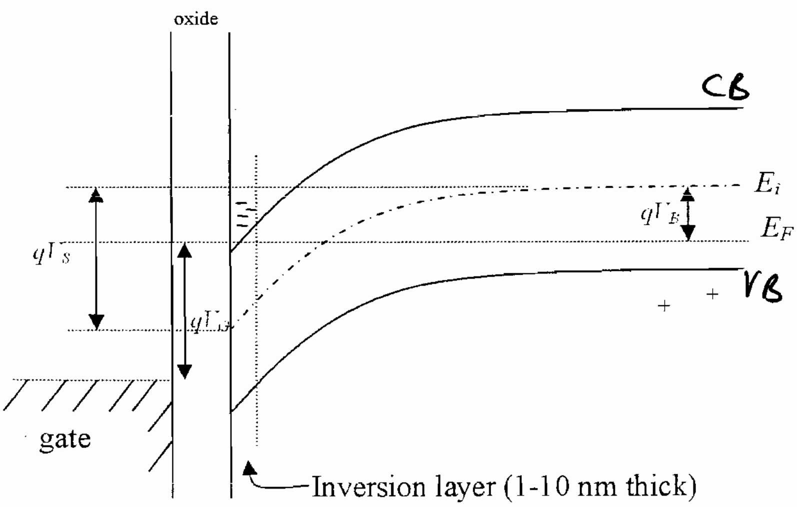
Equilibrium – no bias

3



Depletion – V_{GS} positive

3



Inversion – V_{GS} V_T

3

Q1 (cont.)

(b) Main variation in V_T is through $N_A^{\frac{1}{2}}/C_{ox}$ term. C_{ox} increases as the oxide thickness reduces due to scaling. N_A must increase to reduce depletion regions in line with scaling. Overall $N_A^{\frac{1}{2}}/C_{ox}$ reduces which reduces V_T. Both V_{FB} and V_B are only weakly dependent on N_A and therefore do not influence V_T. 4

V_T needs to be reduced during scaling to minimise power dissipation during switching. 2

As the third term in V_T expression is reduced due to scaling the other terms start to dominate and hence V_T reduces very little. 2

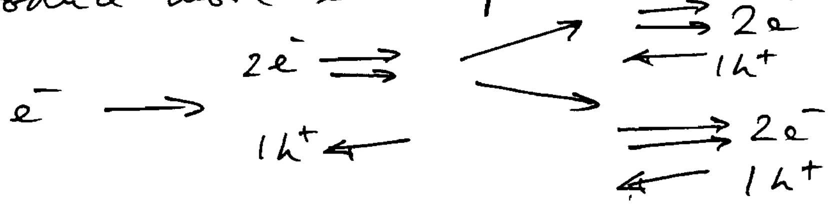
(c) Change in threshold voltage due to oxide charge

$$\Delta V_T = \frac{Q_{ss}}{C_{ox}} = \frac{5\times10^{-7}}{\epsilon/d_{ox}}$$

$$= \frac{5\times10^{-7}\times5\times10^{-8}}{3.45\times10^{-13}}$$

$$= \underline{\underline{0.072\,V}}$$ 3

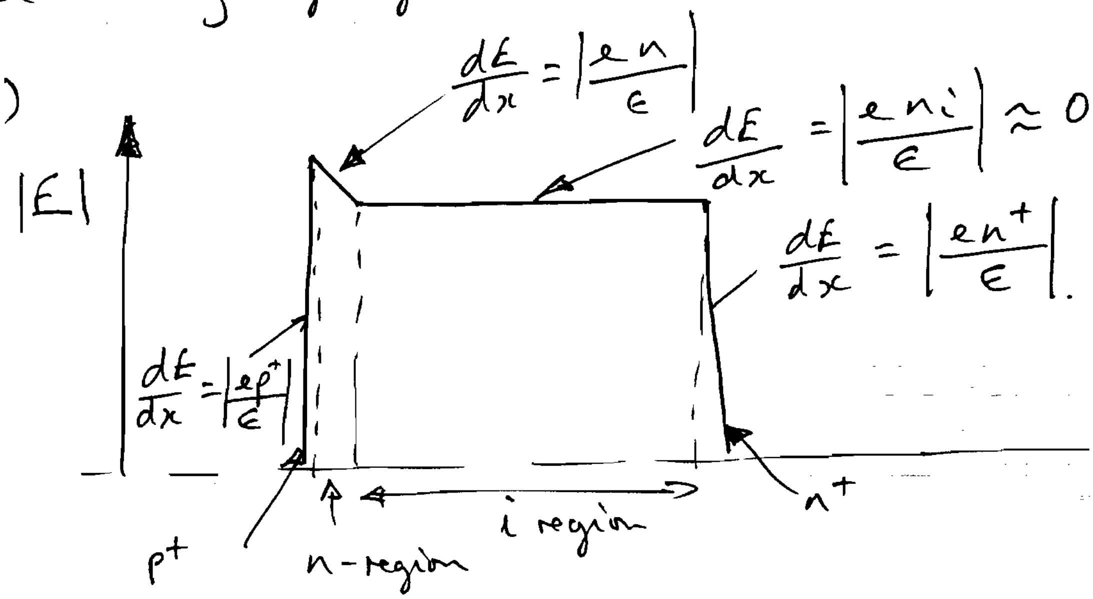
Q2 (a) When electrons gain sufficient energy from an electric field they can create e-h pairs by transferring their kinetic energy to break a crystal bond. Secondary electrons and holes so created are accelerated in turn to produce more e-h pairs.



3

This process is important for small devices since very high fields are encountered. 1

(b)



4

Assumptions from question $\alpha = \beta$ and $=$ const.

$$\therefore \quad 1 - \frac{1}{M_n} = \int_0^W \alpha\, dx = \alpha W$$

$\therefore \quad \alpha W = 1$ for breakdown (i.e. $M_n \to \infty$) 2

i.e. $3.8 \times 10^7 \exp\left(\frac{-3\times10^6}{E_n}\right) \times 0.05 \times 10^{-6} = 1$

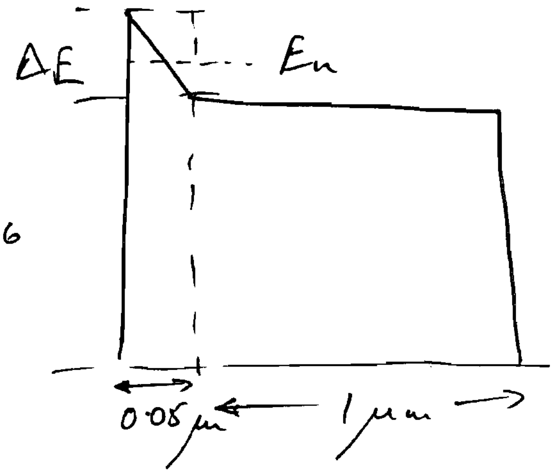
$$\Rightarrow \frac{3\times10^6}{E_n} = \ln\left[3.8\times10^7 \times 0.05\times10^{-6}\right]$$ 2

$$\Rightarrow \quad E_n = \frac{3\times10^6}{\ln\left[3.8\times10^7\times0.05\times10^{-6}\right]} = \underline{4.67\times10^6\ \mathrm{V/m}}$$

Q 2 (cont.)

Now $\Delta E = \frac{e n}{\epsilon} dx$

(from Poisson's Equation)



$$= \frac{1.6\times10^{-19} \times 3\times10^{21} \times 0.05\times10^{-6}}{1.17\times10^{-10}}$$

$$= \underline{2.05\times10^{6}\ V/m} \qquad 2$$

Breakdown voltage = area under $E(x)$ diagram

$$= E_n \times 0.05\times10^{-6} + \left(E_n - \frac{\Delta E}{2}\right)\times 1\times10^{-6}.$$

$$= 0.2 + 3.65 = \underline{\underline{3.85\ V}} \qquad 4$$

Frequency - take electron velocity $1\times10^{5}\ ms^{-1}$

$$\therefore \underline{\text{frequency}} = \frac{1}{\tau} = \frac{1\times10^{5}}{1\times10^{-6}} = 10^{11}\ Hz$$

$$= \underline{\underline{100\ GHz}}$$

2

Q3

(a) $r_{bb'}$ = base access resistance (lateral resistance between base contact and centre of the emitter)

2

$$r_\pi = \frac{\partial I_E}{\partial V_{BE}} = \frac{kT}{qI_E}$$ = input dynamic resistance of EB junction 2

r_o = output conductance $\left(\frac{\partial I_c}{\partial V_{CE}}\right)^{-1}$ – due to Early Effect 2

In an HBT structure:

$r_{bb'}$ is greatly reduced since very high doping in the base is possible without reducing the gain.

r_o is increased since depletion of the base (Early effect) greatly reduced due to high doping there.

r_π is unaffected.

<u>benefits</u>

f_{max} is increased due to reduced $r_{bb'}$

Increased r_o results in a more linear amplification

2

Q3 (cont.)

(b) $\underline{\tau_{BE}}$ – delay in charging C_{BE} capacitance through intrinsic diode (emitter-base) resistance. 2

$$\tau_{BE} = \frac{dQ_{BE}}{dI_E} = C_{BE}\frac{\partial V_{BE}}{\partial I_E} = \frac{kT}{qI_E}\cdot C_{BE}$$

$\underline{\tau_B}$ – base transit delay – time for electrons to diffuse through the base.

equivalent capacitance $C_B = \dfrac{\partial Q_B}{\partial V_{BE}}$ 2

where Q_B is the excess base charge.

$\underline{\tau_{BC}}$ – delay in charging C_{BC} through the intrinsic emitter-base diode resistance plus emitter and collector resistance since current must also flow through these resistors 2

i.e. $\tau_{BC} = \left(\dfrac{kT}{qI_E} + r_e + r_c\right) C_{BC}$.

$\underline{\tau_C}$ – collector transit time – same argument as τ_B i.e. equivalent capacitance

$= \dfrac{\partial Q_C}{\partial V_{BE}}$ Q_C – charge in transit in collector 2

Since of of this charge is driven by V_{BE}, the total delay can be represented by $C_{b'e}$ which includes the sum of all the capacitance delays above. 2

4 (a) transconductance $g_m = \frac{\partial I_D}{\partial V_{GS}}$ (definition)

$$= \frac{Z \mu C_{ox}}{L} \left(V_{GS} - V_T\right) \qquad 2$$

$\underline{f_T}$ gain $= \frac{\text{output current}}{\text{input current}} = \frac{g_m V_{GS}}{V_{GS}\, \omega\, C_{ox} \times Z \times L}$

$$= 1 \quad \text{at} \quad f = f_T \qquad 1$$

$$\Longrightarrow f_T = \frac{g_m}{2\pi C_{ox} Z L} = \frac{\cancel{Z} \mu \cancel{C_{ox}}}{2\pi \cancel{C_{ox}} \cancel{Z} L^2}\left(V_{GS} - V_T\right)$$

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

These expressions assume that the velocity of the electrons will continue to rise as $v = \mu E$ but in fact the velocity saturates at high fields when gate lengths are short, hence g_m and f_T will not rise as fast as predicted above as L shrinks. 2

Reductions in I_D and g_m due to velocity saturation can be compensated by increasing C_{ox}. Also the threshold voltage can be reduced as C_{ox} increases since the former will increase as the channel doping increases during the shrinking process. 3

(b) Transit-time $f_T = \frac{1}{2\pi \tau}$ $\quad \tau = \frac{v}{L}$

Just at the point of pinch-off (saturation)

$V_{DS} = V_{GS} - V_T = 5 - 2 = 3\,V$ 1

$\underline{5\,\mu m \text{ gate}}$ Electric field $E = \frac{3}{5 \times 10^{-6}}$

$$= 6 \times 10^5\, V m^{-1} = 6\, kV/cm$$

4 (cont.) velocity $v = 1\times10^5\left(\frac{6}{7+6}\right)$ ms^{-1} $= 0.46\times10^5$ ms^{-1}

$$\therefore f_T(5\mu m) = \frac{v}{2\pi L} = \frac{0.46\times10^5}{2\pi\times5\times10^{-6}}$$

$$= \underline{1.46\text{ GHz}}.\quad 2$$

0.1μm gate $\quad E = \frac{3}{1\times10^{-7}} = 300$ kV/cm

$$v = 1.5\times\frac{300}{307} = 0.977\times10^5 \text{ ms}^{-1}$$

$$\therefore f_T(0.1\mu m) = \frac{0.977\times10^5}{2\pi\times0.1\times10^{-6}} = \underline{155\text{ GHz}}\quad 2$$

f_T values increase faster than $\propto\frac{1}{L}$ due to velocity increasing towards saturation.

c. Full marks to this section given for reasoned arguments showing knowledge of the issues (2 only required).
May include: 2 marks each point

- Cost of setting up process equipment and facilities
- Intolerable S-D leakage currents for $L < 9$nm
- Inability to develop "high-k" dielectrics of sufficient quality and reliability.
- Control of small dimensions to required tolerances becomes impossible.
- Non-available high conductivity interconnect metal and "low-k" dielectrics.
- Accurate high frequency device and circuit models not available.
- Front-end processing models not available