UNIVERSITY OF CALIFORNIA, BERKELEY
College of Engineering
Department of Electrical Engineering and Computer Sciences

EE 130: IC Devices

Fall 2001

FINAL EXAMINATION

NAME: SOLUTIONS ______________ ______________
(print) Last First Signature

STUDENT ID#: ______________

INSTRUCTIONS:

1. Use the values of physical constants provided below.
2. SHOW YOUR WORK. (Make your methods clear to the grader!)
3. Clearly mark (underline or box) numeric answers. Specify the units on answers whenever appropriate.

Physical Constants

Description	Symbol	Value
electronic charge	q	1.6×10^{-19} C
electron rest mass	m_o	9.1×10^{-31} kg
thermal voltage at 300K	kT/q	0.026 V
Boltzmann's constant	k	8.62×10^{-5} eV/K

$(kT/q)\ln(10) = 0.060$ V at $T = 300$K

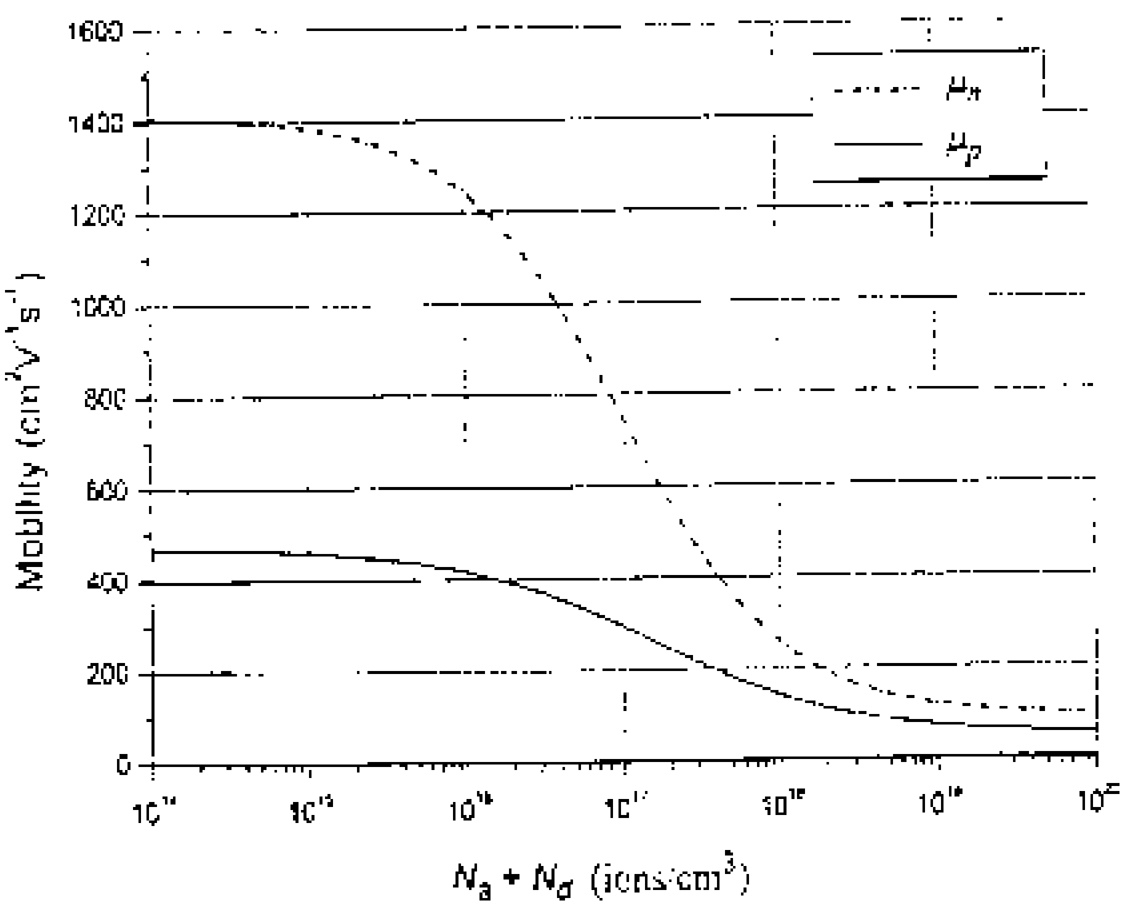
Properties of SiO_2 at 300K

Description	Symbol	Value
band gap	E_g	9 eV
permittivity	ε_{SiO2}	3.45×10^{-13} F/cm
electron affinity	χ_{SiO2}	0.95 V

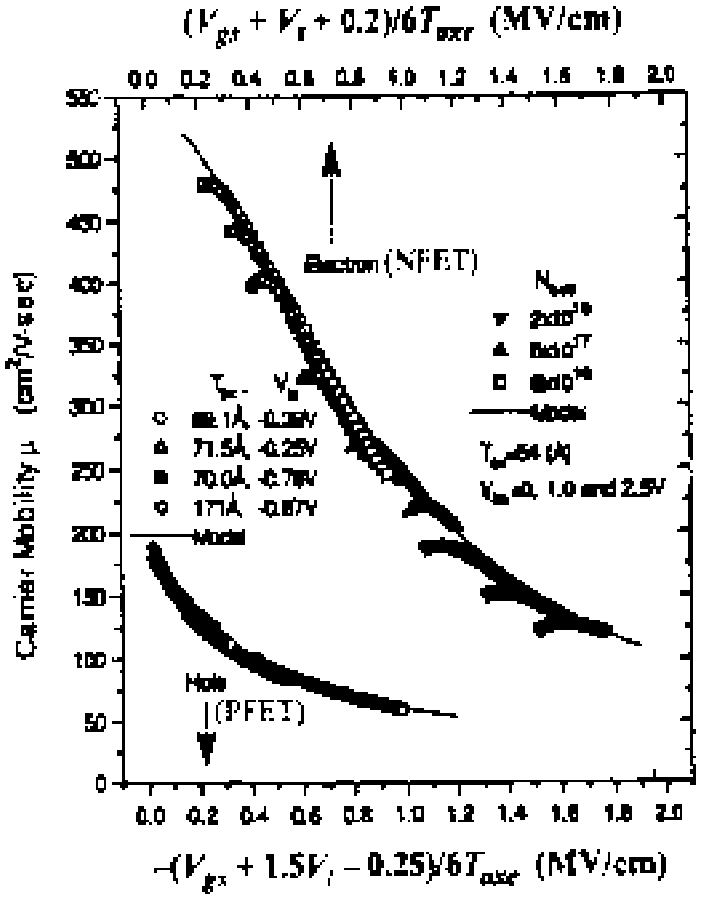
Properties of Silicon at 300K

Description	Symbol	Value
band gap	E_g	1.12 eV
intrinsic carrier density	n_i	10^{10} cm^{-3}
permittivity	ε_S	1.0×10^{-12} F/cm
electron affinity	χ_{Si}	4.05 V

Electron and Hole Mobilities in Silicon at 300K



Field-Effect Mobilities in Si at 300K



SCORE:

1 ________ / 30

2 ________ / 30

3 ________ / 35

4 ________ / 40

5 ________ / 25

6 ________ / 40

Total: ________ / 200

Problem 1: Semiconductor Fundamentals [30 points]
Consider an uncompensated, uniformly doped Si sample of length 1 mm, maintained under equilibrium conditions at $T = 300\text{K}$, with electron concentration $n = 10^4\ \text{cm}^{-3}$.

a) What is the hole concentration p? **[3 pts]**

Under equilibrium conditions, $pn = n_i^2$

$$p = \frac{n_i^2}{n} = \frac{10^{20}}{10^4} = \underline{\underline{10^{16}\ \text{cm}^{-3}}} = N_A - N_D$$

$$\Rightarrow N_A = 10^{16}\text{cm}^{-3},\ N_D = 0$$

(uncompensated material)

b) Calculate the resistivity of this sample. **[5 pts]**

$$\rho = \frac{1}{q\mu_n n + q\mu_p p} = \frac{1}{q\mu_p p} \quad \text{since } p \gg n$$

From mobility vs. dopant concentration plot, $\mu_p = 420\ \text{cm}^2/\text{V}\cdot\text{s}$
for $N_A + N_D = 10^{16}\ \text{cm}^{-3}$. $\mu_n = 1250\ \text{cm}^2/\text{V}\cdot\text{s}$

$$\rho = \frac{1}{(1.6\times10^{-19})(420)(10^{16})} \cong \boxed{1.5\ \Omega\text{-cm}}$$

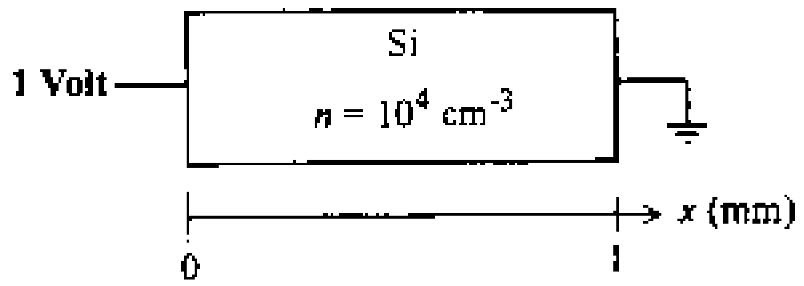
c) If the minority-carrier lifetime in this sample is 1 µs, what is the minority-carrier diffusion length? **[5 pts]**

$$\tau_n = 10^{-6}\text{s}$$

$$D_n = \frac{kT}{q}\mu_n = 0.026\,(1250) = 32.5\ \text{cm}^2/\text{s}$$

$$L_n = \sqrt{D_n\tau_n} = \sqrt{32.5\times10^{-6}} = 5.7\times10^{-3}\text{cm} = \underline{\underline{57\ \mu\text{m}}}$$

d) Suppose a potential difference of 1 V is applied across the sample as shown below:



Uniform sample

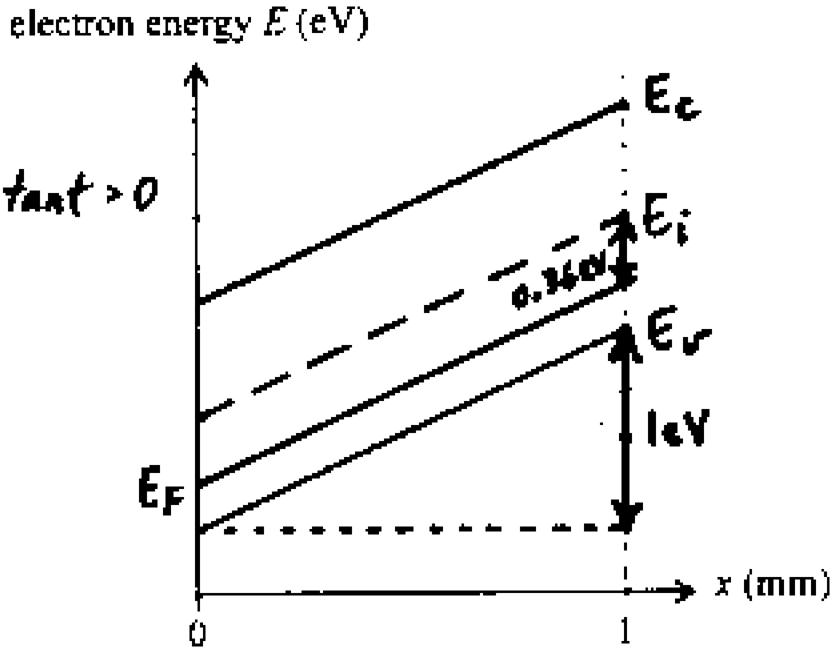
=> uniform electric field

$$\mathcal{E} = \frac{1\text{V}}{1\text{mm}} = 10\ \text{V/cm}$$

very low!

i) Sketch the non-equilibrium energy-band diagram on the plot below, showing E_c, E_v, E_i and E_F as a function of distance x. Indicate the position of E_F with respect to E_i. [7 pts]

$$\mathcal{E} = \frac{1}{q}\frac{dE_c}{dx} = \text{constant} > 0$$



Since $\mathcal{E}$ is very low, the sample can be approximated to be in equilibrium, and we can draw a line for E_F.

$$E_i - E_F = kT\ln\left(\frac{p}{n_i}\right) = kT\ln\left(\frac{10^{16}}{10^{10}}\right) = 6\,kT\ln(10) = 6 \times 0.06 = \underline{\underline{0.36}}$$

ii) What is the resultant electron drift velocity? (Be careful to indicate the proper sign!) [5 pts]

$$v_d = -\mu_n \mathcal{E} = -1250 \times 10 = \boxed{-125\ \text{[illegible]m/s}}$$

(velocity is negative because electrons are moving in the $-x$ direction.)

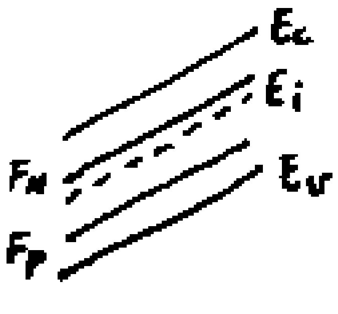
iii) Describe qualitatively how your energy-band diagram in part (i) would change if the biased sample were to be uniformly irradiated with light, resulting in an electron-hole-pair generation rate $G_L = 10^{20}$ EHP/cm^3-s. [5 pts]

Excess hole and electron concentrations: $\Delta p = \Delta n = G_L \tau_n$

$= (10^{20})(10^{-6}) = 10^{14}$ cm^{-3}

$\Delta p << p_0$ so $p = p_0 = 10^{16}$ cm^{-3} → quasi-Fermi level for holes (F_p) will be unchanged: $E_i - F_p = \underline{0.36\ \text{eV}}$

$\Delta n >> n_0$ so $n = \Delta n = 10^{14}$ cm^{-3} → quasi-Fermi level for electrons (F_n) will split away from F_p

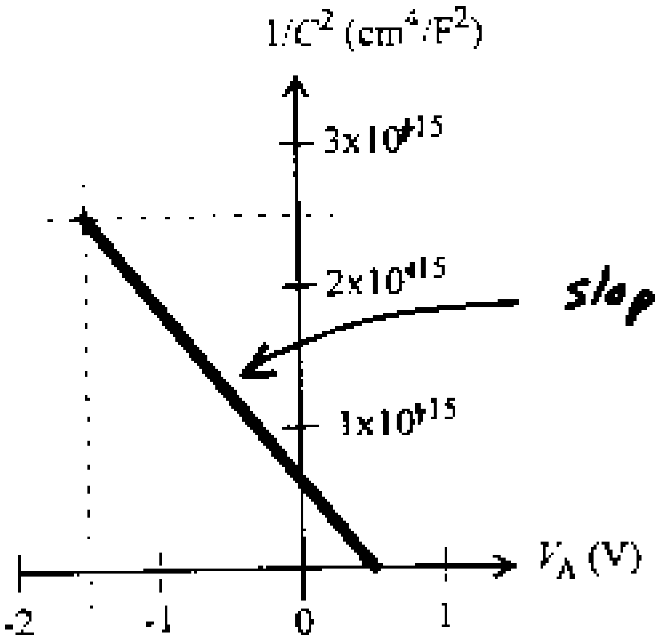


$$F_N - E_i = kT\ln\left(\frac{n}{n_i}\right) = kT\ln\left(\frac{10^{14}}{10^{10}}\right) = 4\,kT\ln(10) = 4 \times 0.06 = \underline{\underline{0.24}}$$

Problem 2: Metal-Semiconductor Contact [30 points]

A Schottky diode formed on n-type Si at T = 300K yields the $1/C^2$ vs. V_A plot shown below. (C is the small-signal capacitance per cm^2.)

$$\frac{1}{C^2} = \frac{2}{qN_D\varepsilon_{Si}}(V_{bi}-V_A)$$



$$\text{slope} = \frac{-2.5\times10^{+15}}{2} = -1.25\times10^{+15}$$

a) What is the built-in potential V_{bi}? [3 pts]

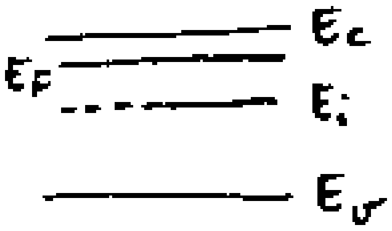
$\frac{1}{C^2} = 0$ when $V_A = V_{bi}$ $\Rightarrow$ $\boxed{V_{bi} = 0.5\text{ V}}$

b) What is the doping concentration N_D in the Si? [6 pts]

$$\text{Slope of curve} = -\frac{2}{qN_D\varepsilon_{Si}} = -1.25\times10^{+15}$$

$$N_D = \frac{2}{(1.6\times10^{-19})(10^{-12})(1.25\times10^{+15})} = \boxed{10^{16}\text{ cm}^{-3}}$$

$$E_F - E_i = kT\ln\left(\frac{10^{16}}{10^{10}}\right) = 6\times0.06 = 0.36\text{eV}$$



(flat band diagram for Si)

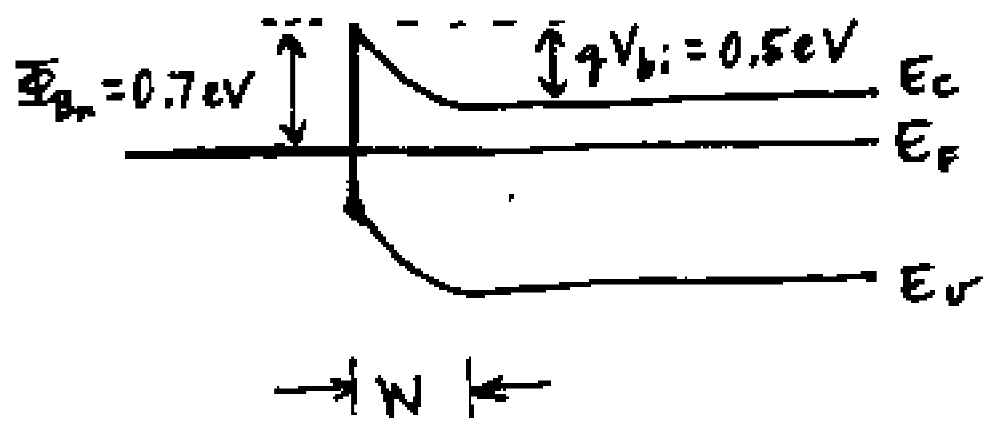
$$(E_c - E_F)_{FB} = \tfrac{1}{2}E_g - (E_F - E_i) = 0.56 - 0.36 = 0.2\text{ eV}$$

c) What is the Schottky barrier height Φ_{Bn}? [6 pts]

$$qV_{bi} = \Phi_{Bn} - (E_c - E_F)_{FB}$$

$$\Phi_{Bn} = qV_{bi} + (E_c - E_F)_{FB} = 0.5\text{eV} + 0.2\text{eV} = \boxed{0.7\text{ eV}}$$

d) Draw the equilibrium energy-band diagram for the Schottky diode, showing E_c, E_v, E_i and E_F in the Si, and labelling Φ_{Bn}, V_{bi} and the depletion width W. (Numerical values are required.) **[12 pts]**



$$W = \sqrt{\frac{2\varepsilon_{Si}V_{bi}}{qN_D}} = \sqrt{\frac{2(10^{-12})(0.5)}{(1.6\times10^{-19})(10^{16})}} = 2.5\times10^{-5}\text{ cm} = \underline{\underline{0.25\ \mu m}}$$

e) Referring to the energy-band diagram in part (d), explain how an ohmic contact can be practically achieved by increasing the dopant concentration in the Si. [3 pts]

$$W \propto \frac{1}{\sqrt{N_D}}$$

As N_D is increased, W decreases.

For very high concentrations N_D, W can be small enough so that electrons can directly tunnel through the potential barrier very easily.

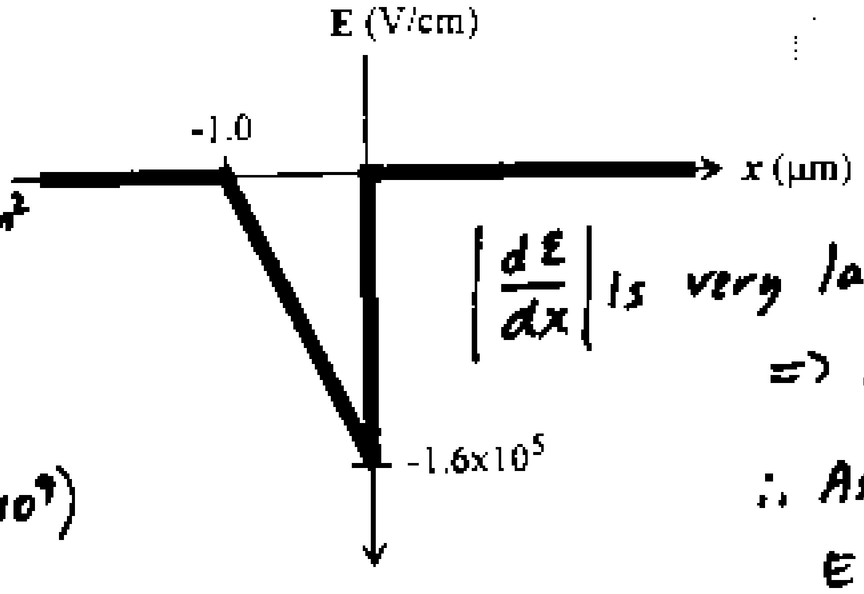
$\Rightarrow$ low-impedance (ohmic) contact

Problem 3: p-n Junction Diode [35 points]

Given the following electric-field distribution inside an ideal long-base Si diode maintained at $T = 300$K:

$$\frac{d\mathcal{E}}{dx} = \frac{-1.6\times10^{5}}{10^{-4}} = -1.6\times10^{9}\ \text{V/cm}^2 = \frac{-qN_A}{\varepsilon_{Si}}$$

$$N_A = -\frac{\varepsilon_{Si}}{q}\frac{d\mathcal{E}}{dx} = \frac{-10^{-12}}{1.6\times10^{-19}}\left(-1.6\times10^{9}\right) = 10^{16}\ \text{cm}^{-3}$$



$\left|\frac{d\mathcal{E}}{dx}\right|$ is very large (as compared to p-side)

$\Rightarrow N_D \gg 10^{16}\ \text{cm}^{-3}$

∴ Assume degenerately doped

$E_F = E_C$, so $E_F - E_i = \frac{1}{2}E_g$

a) What is the built-in potential V_{bi} of this junction? [7 pts]

$$qV_{bi} = (E_i - E_F)_{p\text{-side}} + (E_F - E_i)_{n\text{-side}}$$

$$= 0.36\ \text{eV} + 0.56\ \text{eV} = 0.92\ \text{eV}$$

$$\boxed{V_{bi} = 0.92\text{V}}$$

$$\boxed{\begin{aligned}(E_i - E_F)_{p\text{-side}} &= kT\ln\frac{N_A}{n_i} \\ &= kT\ln\frac{10^{16}}{10^{10}} \\ &= 6\times kT\ln(10) \\ &= 6\times0.06 \\ &= 0.36\text{eV}\end{aligned}}$$

b) What is the applied bias V_A for the given electric field distribution? [5 pts]

$$V_{bi} - V_A = -\int_{-x_p}^{x_n}\mathcal{E}\,dx = -\frac{1}{2}(10^{-4})(-1.6\times10^{5}) = 8\ \text{V}$$

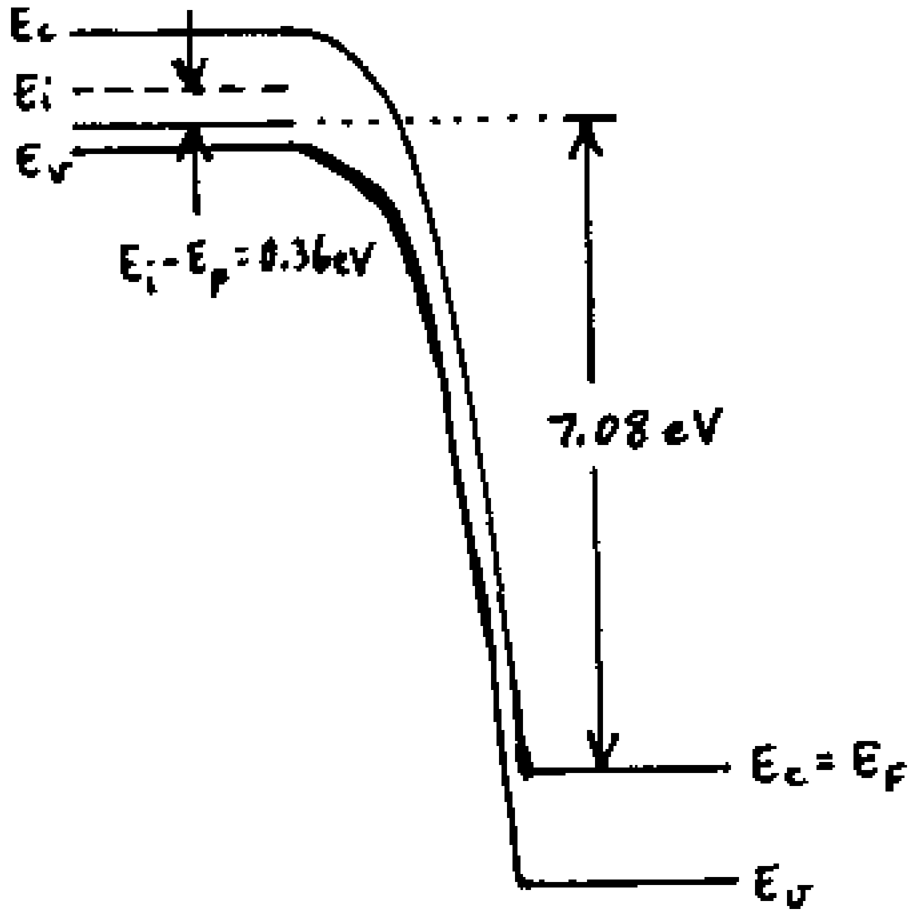
$$\Rightarrow V_A = V_{bi} - 8 = 0.92 - 8 = \boxed{-7.08\text{V}}$$

c) What is the small-signal junction capacitance (in units of F/cm^2) at this bias? [3 pts]

Since the diode is reverse biased, the diffusion capacitance is negligible compared with the depletion capacitance.

$$C = C_{dep} = \frac{\varepsilon_{Si}}{W} = \frac{10^{-12}}{10^{-4}} = \boxed{10^{-8}\ \text{F/cm}^2}$$

d) Draw the energy-band diagram (showing E_c, E_i, E_v, E_{Fn}, and E_{Fp}), indicating the values of $|E_F - E_i|$ in the quasi-neutral regions, as well as the vertical separation between E_{Fp} and E_{Fn}. [12 pts]



e) Given that the minority-carrier lifetime is 1 μs in the lightly doped side of the junction, what is the current density flowing in the diode? [5 pts]

$$J = J_0 \left(e^{qV_A/kT} - 1\right) \simeq -J_0 \qquad \text{since } V_A << 0$$

$$J_0 = q \frac{D_N}{L_N} \frac{n_i^2}{N_A} = 1.6\times10^{-19}\left(\frac{32.5}{57\times10^{-4}}\right)\left(\frac{10^{20}}{10^{16}}\right) = 9.1\times10^{-12}\ A/cm^2$$

$\mu_n = 1250\ cm^2/V\cdot s$ from mobility vs. dopant concentration plot

$D_N = \frac{kT}{q}\mu_n = 0.026\,(1250) = 32.5\ cm^2/s$

$L_N = \sqrt{D_N \tau_N} = 57\times10^{-4}\ cm$ (from Problem 1c)

$\boxed{J = -9.1\ pA/cm^2}$

f) Suppose that the critical electric field for breakdown is $\mathcal{E}_{CR} = 5\times10^5$ V/cm. What is the dominant mechanism by which breakdown will occur as the reverse bias is increased? Explain briefly. [3 pts]

$\mathcal{E}_{CR} > 1.6\times10^5\ V/cm$, so $V_{BR} > 7.08\ V$

$\Rightarrow$ depletion width will be greater than 1 μm at breakdown.

$\Rightarrow$ tunneling is not likely to occur across the depletion region

$\Rightarrow$ Dominant breakdown mechanism will be avalanching or impact ionization

Problem 4: Bipolar Junction Transistor [40 points]

a) The base dopant concentration N_B is a critical parameter which affects BJT performance. Describe the N_B design tradeoff by explaining why N_B should neither be too low (give 2 reasons) nor too high (give 2 reasons). **[8 pts]**

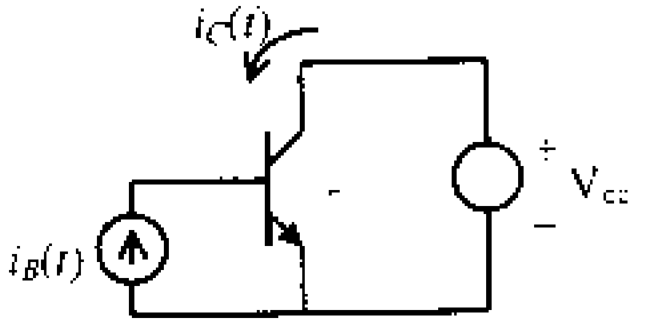
N_B should not be too low to ensure

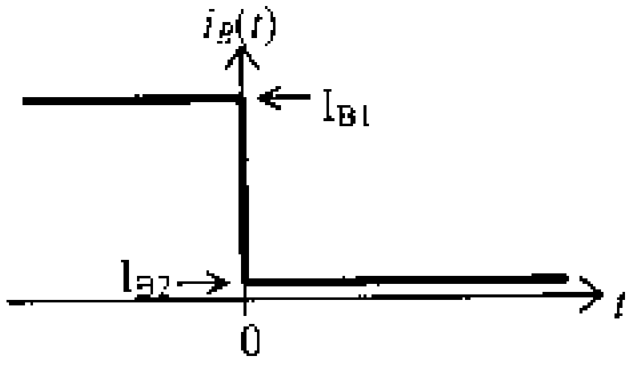
- large Early voltage (small base-width modulation effect)
- large punchthrough voltage

N_B should not be too high to ensure

- high emitter injection efficiency γ (needed for high gain β_{dc})
- "low" (not too high) base-emitter junction capacitance and base-collector junction capacitance (needed for high f_T)

b) Consider a npn BJT with minority-carrier lifetime in the base τ_B, which is biased in active mode with base current $i_B = I_{B1}$ for all times $t < 0$ and dropping suddenly to $I_{B2} < I_{B1}$ for all times $t > 0$:





i) Write an equation describing the rate at which Q_B (the excess minority-charge stored in the quasi-neutral base) changes, for $t > 0$. **[4 pts]**

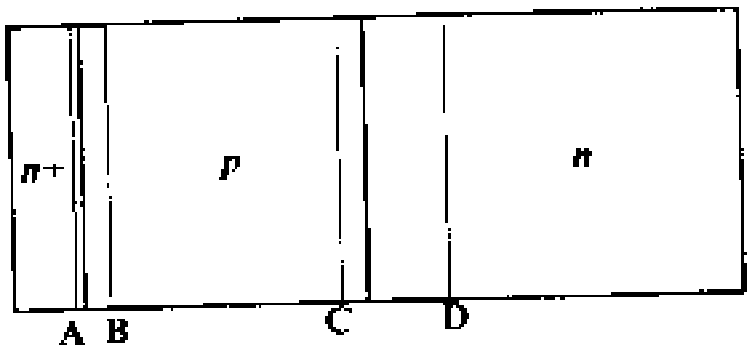
$$\frac{dQ_B}{dt} = I_{B2} - \frac{Q_B}{\tau_B}$$

ii) Considering your answer to part (i), describe 2 ways to achieve a rapid transient response (*i.e.* to make the collector current reach its final value quickly). **[4 pts]**

- minimize τ_B ("kill" minority-carrier lifetime in the base)
- minimize I_{B2}

These will allow $\frac{dQ_B}{dt}$ to be as negative as possible, to quickly remove the minority-carriers from the quasi-neutral base region.

c) Consider an ideal npn silicon BJT of area $A = 10^{-7}$ cm^2 maintained at $T = 300$K, operating at the edge of saturation with $V_{BE} = 0.7$ V and $V_{BC} = 0$ V, so that the width of the quasi-neutral base region is $W = 0.5$ μm and the width of the quasi-neutral emitter region is $W_E = 0.1$ μm. Assume that the emitter and base regions are short ($W << L_B$ and $W_E << L_E$).



Each region of the BJT is uniformly doped: $N_E = 10^{19}$ cm^{-3}, $N_B = 10^{17}$ cm^{-3}, $N_C = 10^{15}$ cm^{-3}. The minority-carrier diffusion constants are $D_E = 2$ cm^2/s, $D_B = 20$ cm^2/s, $D_C = 12$ cm^2/s.

i) What is the common-emitter d.c. current gain, β_{dc}, of this transistor? **[4 pts]**

$$\beta_{dc} = \frac{D_B N_E W_E}{D_E N_B W} = \frac{(20)(10^{19})(0.1\times10^{-4})}{(2)(10^{17})(0.5\times10^{-4})} = \boxed{200}$$

ii) Calculate the base transit time τ_t. (Assume that electrons flow in the quasi-neutral base region by diffusion only.) [**3 pts**]

$$\tau_t = \frac{W^2}{2D_B} = \frac{(0.5\times10^{-4})^2}{2(20)} = 6.25\times10^{-11}\text{ s} = \boxed{62.5\text{ ps}}$$

iii) Assume that the dominant component of base current is the current required to supply holes for recombination (in the quasi-neutral base region) with electrons injected from the emitter, *i.e.* $I_B = Q_B/\tau_B$ where Q_B is the excess minority-charge stored in the quasi-neutral base. Estimate the minority-carrier lifetime in the base τ_B. **[4 pts]**

$$I_B = \frac{Q_B}{\tau_B} \qquad I_c = \frac{Q_B}{\tau_t} \qquad \frac{I_c}{I_B} = \beta_{dc} = 200$$

$$\frac{(Q_B/\tau_t)}{(Q_B/\tau_B)} = \frac{\tau_B}{\tau_t} = \beta_{dc}$$

$$\tau_B = \beta_{dc}\,\tau_t = 200\,(62.5\times10^{-}\,)$$

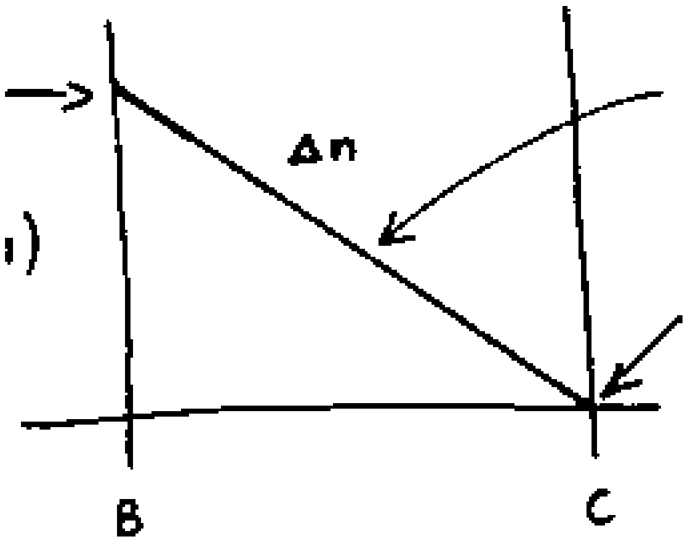
$$= \underline{\underline{12.5\text{ ns}}}$$

iv) Sketch the excess minority carrier concentration profile in the quasi-neutral base region, indicating the concentrations at the edges of the depletion regions (locations B and C in the diagram on the previous page). [4 pts]

$$\Delta n = \frac{n_i^2}{N_B}\left(e^{qV_{BE}/kT} - 1\right) \longrightarrow$$

$$= \frac{10^{20}}{10^{17}}\left(e^{0.7/0.026} - 1\right)$$

$$= \underline{\underline{4.9 \times 10^{14}\,\mathrm{cm}^{-3}}}$$



linear function of distance, since $W \ll L_B$

$$\Delta n = \frac{n_i^2}{N_B}\left(e^{qV_{BC}/kT} - 1\right) = \underline{\underline{0}}$$

v) What is the transconductance, g_m? [5 pts]

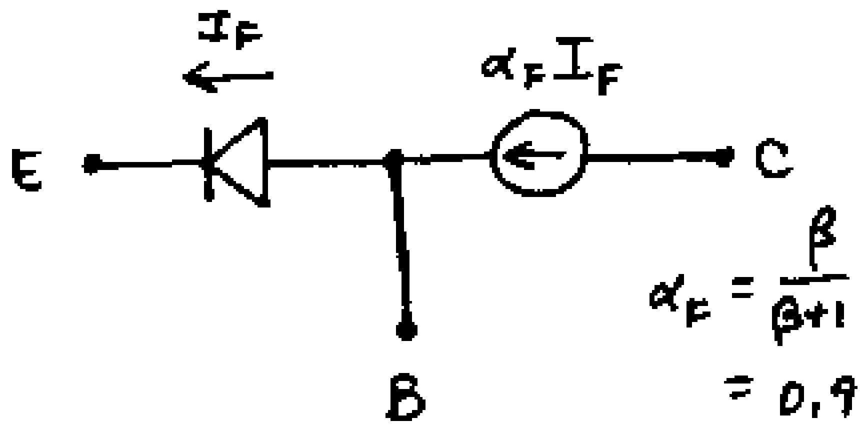
$$L_B = \sqrt{D_B \tau_B} = \sqrt{(20)(12.5\times10^{-9})} = 5\times10^{-4}\,\mathrm{cm} = 5\,\mu\mathrm{m} \gg W$$

$$I_C = \frac{qAD_Bn_i^2}{WN_B}\left(e^{qV_{BE}/kT} - 1\right) = \underbrace{\frac{(1.6\times10^{-19})(10^{-7})(20)(10^{20})}{(0.5\times10^{-4})(10^{17})}}_{6.4\times10^{-18}\,A}\left(e^{0.7/0.026} - 1\right)$$

$$\boxed{= 3.2\,\mu A}$$

$$g_m = \frac{I_C}{(kT/q)} = \frac{3.2\times10^{-6}}{0.026} = \boxed{1.23\times10^{-4}\,\text{Siemens}}$$

vi) Draw the simplified Ebers-Moll model for this BJT operating at the edge of saturation ($V_{BE} > 0$, $V_{BC} = 0$). Indicate the values of the Ebers-Moll parameters. [4 pts]



$$\alpha_F = \frac{\beta}{\beta+1} = \frac{200}{201} = \underline{\underline{0.995}}$$

Since $V_{BC} = 0$, $I_R \propto \left(e^{qV_{BC}/kT} - 1\right) = 0$

and $\alpha_R I_R = 0$

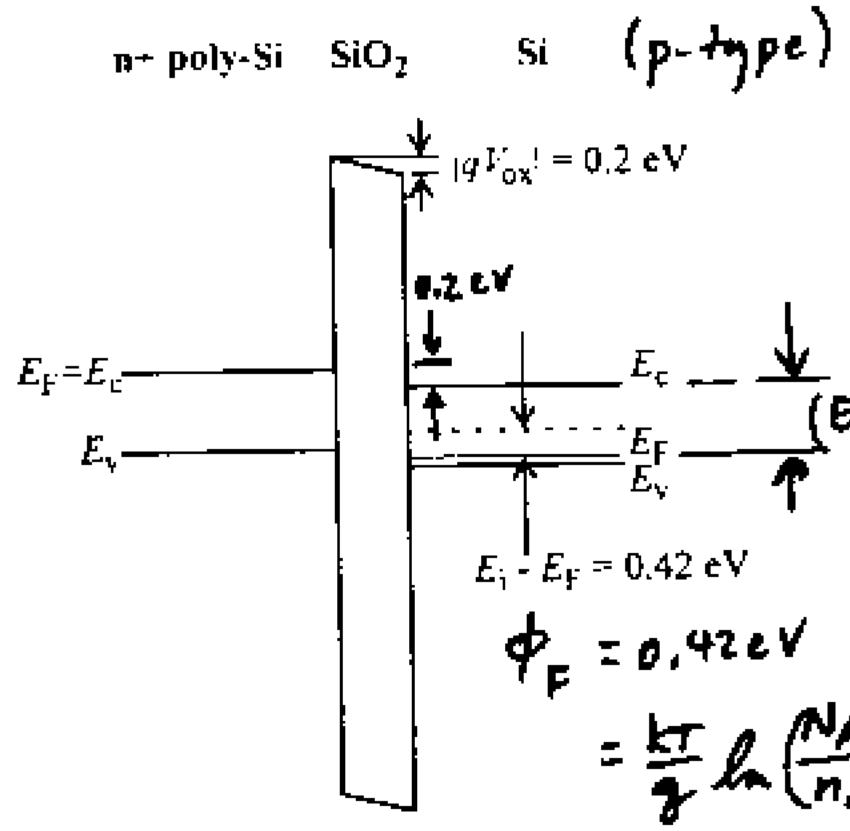
⇒ no current flows in the I_R and $\alpha_R I_R$ branches of the Ebers-Moll model

⇒ these branches can each be replaced by an open circuit.

$$I_F = I_{F0}\left(e^{qV_{BE}/kT} - 1\right)$$

$$I_{F0} = \frac{qAD_Bn_i^2}{WN_B} = \underline{\underline{6.4\times10^{-18}\,A}}$$

Problem 5: Metal-Oxide-Semiconductor Capacitor [25 points]
The flat-band energy-band diagram for an n+ poly-Si gated capacitor of area 10^{-4} µm^2 and T_{oxe} = 3.45 nm, maintained at T = 300K, is shown below:



$$(E_c - E_F)_{Si} = \frac{1}{2}E_g + 0.42\,eV = 0.56\,eV + 0.42\,eV = 0.98\,eV$$

$$\phi_F = 0.42\,eV = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

a) What is the flatband voltage V_{FB}? [5 pts]

$$-qV_{FB} = E_{F\,poly\text{-}Si} - E_{F\,Si} = 0.2\,eV + (E_c - E_F)_{\cancel{poly}\,Si} = 0.2\,eV + 0.98\,eV = 1.18\,e$$

$$\boxed{V_{FB} = -1.18\,V}$$

b) Calculate the oxide fixed charge density Q_F (in units of C/cm^2). [5 pts]

$$C'_{ox} = \frac{\varepsilon_{SiO_2}}{T_{oxe}} = \frac{3.45\times10^{-13}}{3.45\times10^{-7}} = 10^{-6}\,F/cm^2$$

$$V_{FB} = \Phi_M - \Phi_S - \frac{Q_F}{C'_{ox}}$$

$$= \frac{-(E_c - E_F)_{Si}}{q} - \frac{Q_F}{C_{ox}}$$

$$Q_F = C'_{ox}\left[-V_{FB} - \frac{(E_c - E_F)_{Si}}{q}\right] = 10^{-6}\left[-(-1.18) - 0.98\right] = \underline{2\times10^{-7}\,C/cm^2}$$

c) Calculate the threshold voltage, V_T. [6 pts]

This is an NMOS device

$$V_T = V_{FB} + 2\phi_F + \frac{\sqrt{2\varepsilon_{Si}\, q N_A (2\phi_F)}}{C_{ox}}$$

$$= -1.18 + 2(0.42) + \frac{\sqrt{2(10^{-12})(1.6\times10^{-19})(10^{17})(2\times0.42)}}{10^{-6}}$$

$$= -1.18 + 0.84 + 0.16 = \boxed{-0.18\ \text{V}}$$

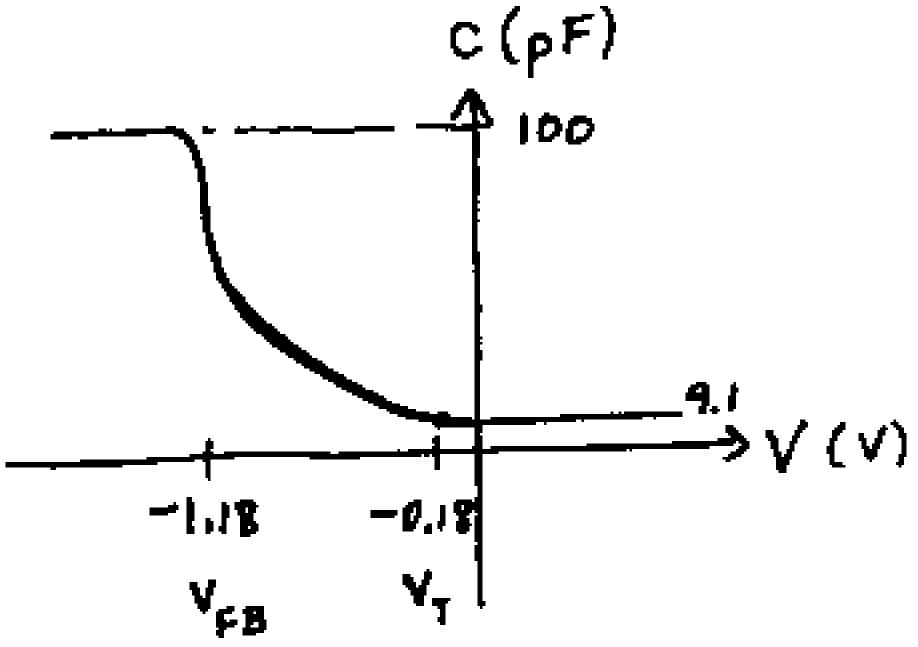
$$W_T = \sqrt{\frac{2\varepsilon_{Si}(2\phi_F)}{qN_A}} = \sqrt{\frac{2(10^{-12})(2\times0.42)}{(1.6\times10^{-19})(10^{17})}} \cong 1.0\times10^{-5}\ \text{cm}$$

d) Draw the high-frequency *C-V* curve for this capacitor, indicating the maximum and minimum capacitance values on your plot, as well as V_{FB} and V_T (consistent with your answers to parts (a) and (c), respectively). [9 pts]

$$C_{max} = C_{ox} = A C_{ox}' = (10^{-4})(10^{-6}) = \underline{\underline{10^{-10}}}\ \text{F}$$

$$C_{min} = \left[\frac{1}{C_{ox}} + \frac{1}{C_{dep}}\right]^{-1} \qquad C_{dep} = \frac{A\varepsilon_{Si}}{W_T} = \frac{(10^{-4})(10^{-12})}{(10^{-5})} = 10^{-11}\ \text{F}$$

$$C_{min} = \left[\frac{1}{10^{-10}} + \frac{1}{10^{-11}}\right]^{-1} = \underline{\underline{9.1\times10^{-12}}}$$



$$C_{ox} = \frac{\varepsilon_{SiO_2}}{T_{oxe}} = \frac{3.45\times10^{-13}}{5\times10^{-7}} = 6.9\times10^{-} \ F/cm^2$$

Problem 6: MOS Field-Effect Transistor [40 points]

a) In a certain CMOS technology, the electrical oxide thickness is T_{oxe} = 5 nm, the body-effect factor is m = 1.25, and the absolute value of the threshold voltage of a long-channel MOSFET is $|V_T|$ = 0.5 V.

i) Estimate the average inversion-layer electron mobility in an n-channel MOSFET with gate bias V_{GS} = 1.5 V, using the universal effective mobility model. [4 pts]

Effective vertical electric field $\mathcal{E}_{eff} = \dfrac{V_{GS}+V_T+0.2}{6T_{oxe}} = \dfrac{1.5+0.5+0.2}{6\times5\times10^{-7}}$

$$= 7.3\times10^{5}\,V/cm$$

From the field-effect mobility plot, $\bar{\mu}_n = \boxed{300\,cm^2/V\cdot s}$

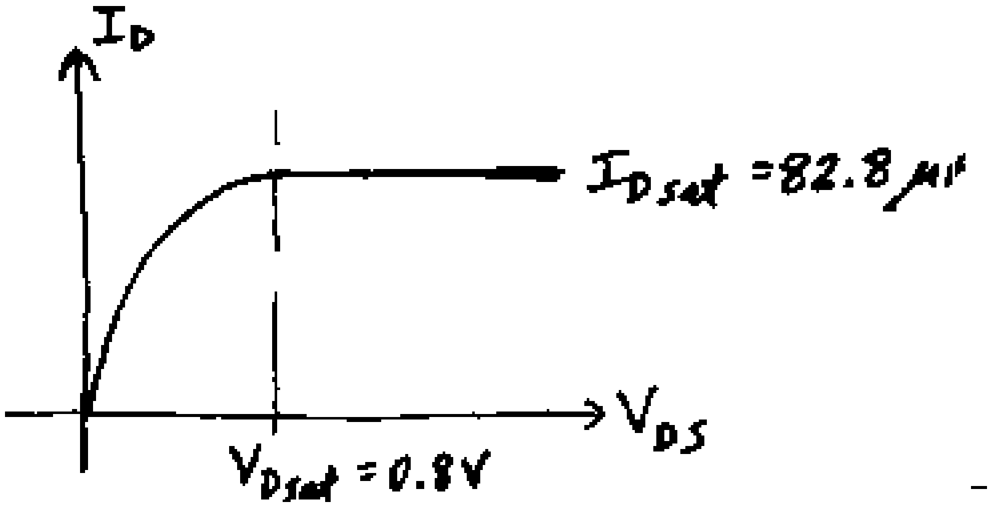
ii) Sketch the I_D vs V_{DS} characteristic for an n-channel MOSFET of channel width Z = 10 μm, channel length L = 10 μm, and gate bias V_{GS} = 1.5 V. Indicate the values of V_{Dsat} and I_{Dsat}. [7 pts]

$$\frac{Z}{L} = 1$$

$$I_{Dsat} = \frac{\bar{\mu}_n C_{ox}}{2m}(V_{GS}-V_T)^2$$

$$= \frac{300\,(6.9\times10^{-7})}{2\,(1.25)}(1.5-0.5)^2 = 82.8\times10^{-6}\,A = \underline{\underline{82.8\,\mu A}}$$

$$V_{Dsat} = \frac{V_{GS}-V_T}{m} = \frac{1.5-0.5}{1.25} = \underline{\underline{0.8V}}$$



iii) For what channel lengths will the effect of velocity saturation be significant (*i.e.* resulting in a reduction in I_{Dsat} by more than a factor of 2)? [5 pts] $v_{sat} = 8\times10^{6}\ cm/s$

$$\mathcal{E}_{sat} = \frac{2v_{sat}}{\bar{\mu}_n} = \frac{2(8\times10^{6})}{300} = 5.3\times10^{4}\,V/cm$$

Velocity saturation effect will be significant when $\mathcal{E}_{sat}L \le \dfrac{V_{GS}-V_T}{m}$

$$L \le \left(\frac{V_{GS}-V_T}{\mathcal{E}_{sat}m}\right) = \frac{(1.5-0.5)}{(5.3\times10^{4})(1.25)} = 1.5\times10^{-5}cm = 0.15\mu m$$

∴ For $\underline{\underline{L \le 0.15\mu m}}$, velocity saturation effect will be significant

b) Short-Answer Questions:

i) Describe the design tradeoff for the threshold voltage V_T of a MOSFET. (Why is it desirable for V_T to be low? Why is it desirable for V_T to be high?) [4 pts]

- We want V_T to be low in order to maximize the transistor current when it is ON (i.e. maximize I_{Dsat}) for fast circuit operation or higher frequency of operation
- We want V_T to be high in order to minimize the transistor leakage current when it is OFF for low static power dissipation

ii) Why does the subthreshold current in a MOSFET depend exponentially on the gate bias V_{GS}? [4 pts]

Below threshold, the drain current is limited by the rate at which carriers can diffuse from the source into the channel. The number of carriers which have enough energy to surmount the potential barrier at the source-channel junction increases exponentially as the height of this potential barrier is reduced linearly. Since the height of this potential barrier is linearly dependent on the gate bias, the subthreshold leakage current is exponentially dependent on the gate bias.

iii) CMOS technology is preferred over NMOS technology because of its lower power consumption and larger noise margins. What are the disadvantages of CMOS technology as compared to NMOS technology? [4 pts]

- Higher process complexity
  due to need to selectively form separate well and source/drain regions
- Susceptibility to latch-up phenomenon
  - parasitic pnpn SCR device could be triggered by voltage or current spikes, switching to the forward-conducti mode; resultant heat (due to high current x voltage -> lots of power dissipation) results in damage to MOSFET devices.

c) Indicate in the table below (by checking the appropriate box for each line) the effect of **decreasing the channel dopant concentration** (N_A) on the performance parameters of an n-channel MOSFET. Provide brief justification for each of your answers. **[12 pts]**

MOSFET parameter	**increases**	**decreases**	**remains the same**	**Brief Explanation of Answer**
Transconductance (g_m)	✓			V_T will decrease; $\bar{\mu}_n$ will Increase $g_m \propto \bar{\mu}_n (V_{GS} - V_T)$
Body effect parameter (γ)		✓		$\gamma \propto \sqrt{N_A}$
Subthreshold swing (S)		✓		$S = 60 mV/dec \times \left(1 + \frac{C_{dep}}{C_{ox}}\right)$ $C_{dep} = \frac{\varepsilon_{si}}{W_T} \propto \sqrt{N_A}$ will decrease