Examination paper for TFE4146 Semiconductor Devices
Date: 24.11.2025
Time: 15:00

Course contact: Erik Folven
Present at the exam location: NO

Permitted examination support material:
C
Specified printed matter:
- Karl Rottmann, Formelsamling/Collection of mathematical formulas.
- Specified simple calculator

OTHER INFORMATION

Read the questions carefully and make your own assumptions. In your answers, explain clearly what assumptions you have made and how you have understood or limited the assignment

If there are direct errors or omissions in the assignment set and you cannot make your own assumptions, please refer to the information about complaints regarding formal errors on the NTNU website “Explanation of grades and appeals”.

SPECIFIC INFORMATION FOR YOUR COURSE

Hand drawings:
For question **20** you are meant to answer on handwritten sheets.
Other questions must be answered directly in Inspera. At the bottom of the question, you will find a seven-digit code. Fill in this code in the top left corner of the sheets you wish to submit.
Please note that only blue or black ballpoint pens are allowed

We recommend that you do this during the exam. If you require access to the codes after the examination time ends, click “Show submission”.
You are responsible for filling in the correct codes on the handwritten sheets. Therefore, read the cover sheet carefully. The Examination Office cannot guarantee that incorrectly completed sheets will be added to your assignment.

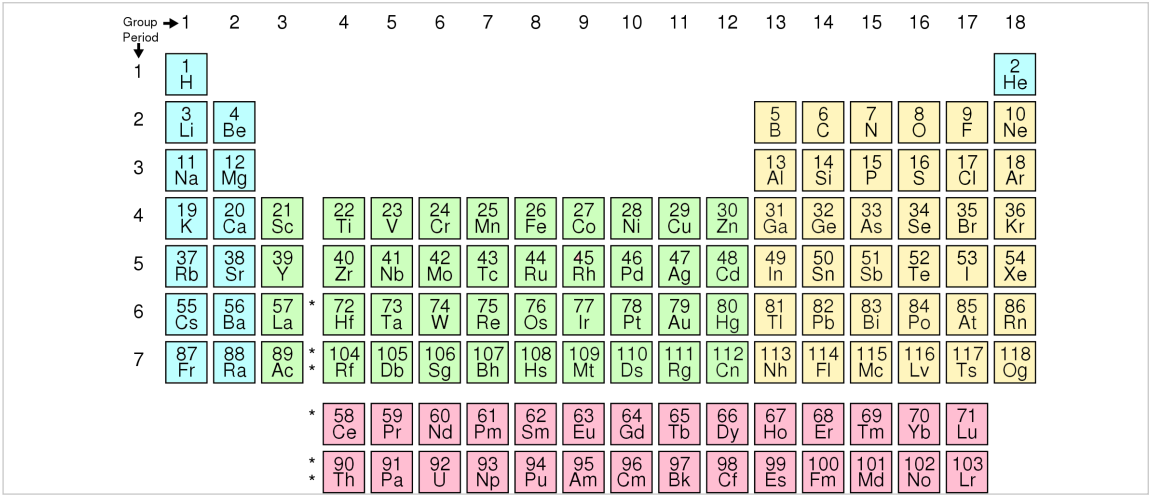
Weighting:
The weighting per question is indicated for each question. Blank and wrong answers are typically treated equally in the scoring of multiple choice questions with only one answer, i.e., in these questions there is no risk in guessing an answer if you do not know the correct answer. In questions with more than one alternative there will typically be negative points for wrong/blank answers, but you may not get less than 0p for the question as a whole.

Notifications:
Any messages during the exam (e.g., in case of errors in the exam set) will be sent out via notifications in Inspera. A notification will appear as a dialog box on the screen. You can find the notification again by clicking on the bell icon at the top right

Withdrawing from the exam:
If you wish to submit a blank test/withdraw from the exam for another reason, go to the menu in the top right-hand corner and click “Submit blank”. This cannot be undone, even if the test is still open.

Access to your answers:
After the exam, you can find your answers under previous tests in Inspera. Be aware that it may take a working day until any hand-written material is available in “previous tests”.

1



Fill in the blanks in the following section of text. Words are suggested for each blank – choose the most appropriate one. (correct: 1p, wrong: -1p, blank: 0p, minimum score: 0p)

We can create mobile carriers in semiconductors by purposely introducing impurities into a crystal. This process is called doping.

We can create a p-doped piece of Ge by replacing some of the atoms in the crystal with Select alternative (Si, B, P)-

atoms. This type of doping is called Select alternative (acceptor doping, intrinsic doping, donor doping)and will

Select alternative (make the crystal negatively charged., make the crystal positively charged., not affect the net charge of the crystal.).

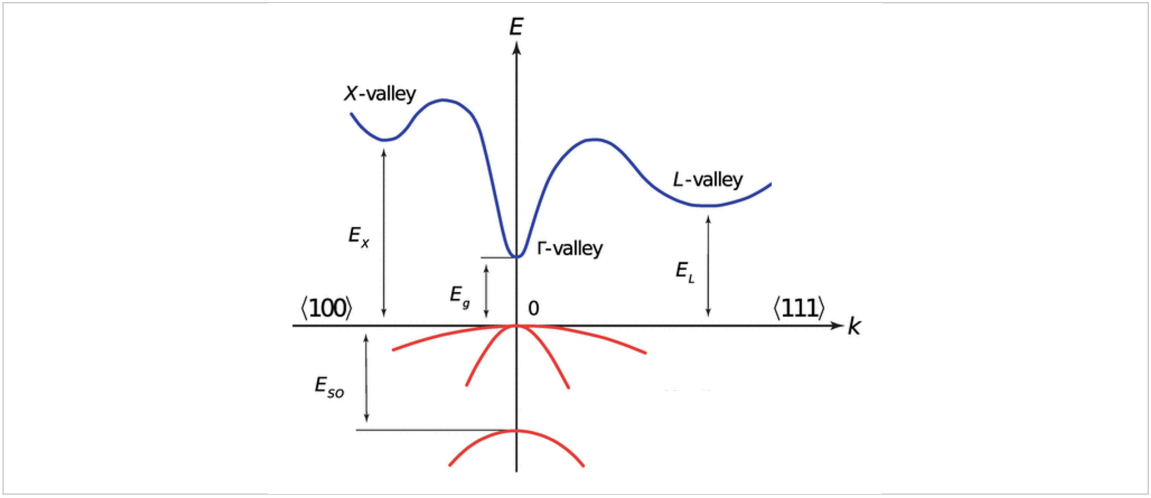
We can create an n-type Ge material by replacing some of the atoms in the crystal with Select alternative (C, In, As)-

atoms. This type of doping will introduce additional Select alternative (electrons, holes) in the crystal and

Select alternative (decrease the Fermi energy in the system., increase the Fermi energy in the system., increase the mobility of the holes in the system, increase the mobility of the electrons in the system.)

Maximum marks: 6

2



The figure shows the band structure of GaAs. In which energy valley of the GaAs conduction band will an electron have the highest mobility?

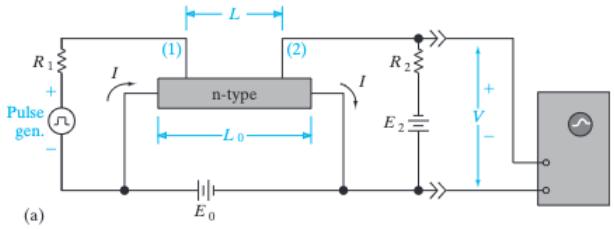
(correct: 2p, wrong: -0p, blank: 0p, minimum score: 0p)

Select one alternative.

- The X-valley
- The Γ-valley
- It will be the same in the entire band.
- The L-valley

Maximum marks: 2

3



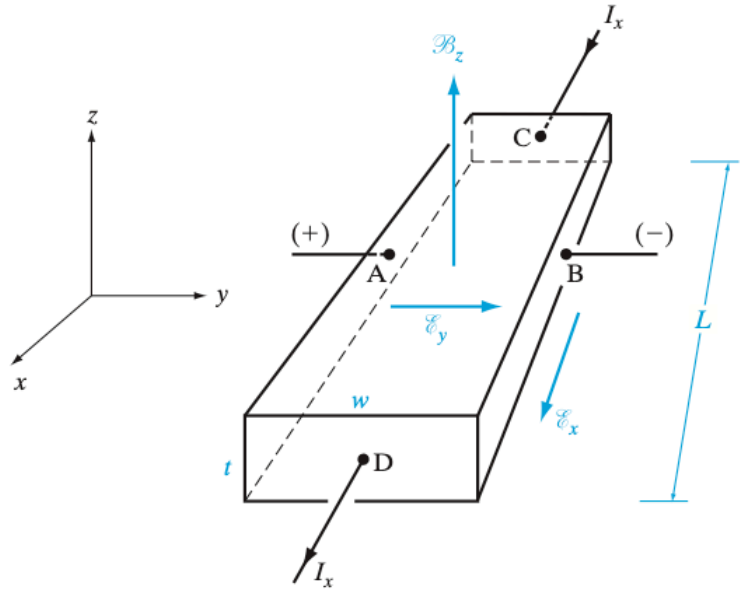
The figure above shows the experimental setup for the Haynes-Shockley experiment.
Which parameters can be measured using the Haynes-Shockley experiment?
(correct: 2p, wrong: -2p, blank: 0p, minimum score 0p)

Select one or more alternatives:

- diffusion coefficient for majority carriers
- mobility of majority carriers
- majority carrier concentration
- mobility of minority carriers
- diffusion coefficient for minority carriers
- minority carrier concentration

Maximum marks: 4

4



The figure above shows the setup for the Hall experiment. The n-type semiconductor bar has a width $w = 0.01\text{cm}$, thickness $t = 10^{-3}\text{cm}$ and length $L = 0.5\text{cm}$. A magnetic field of $B_z = 10^{-4}\text{Wb/cm}^2$ is applied in the direction shown. For a current $I_x = 1\text{mA}$ we have $V_{AB} = -3\text{mV}$ and $V_{CD} = 100\text{mV}$.

Given: The force on a particle with charge q and velocity $\vec{v}$, from a magnetic field $\vec{B}$, is $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$

Find the concentration and mobility of the majority carrier and fill in the numerical answer below.

Majority carrier concentration : [ ] $\cdot 10^{17}\text{cm}^{-3}$

(correct: 4p, wrong: 0p, blank: 0p, minimum score 0p)

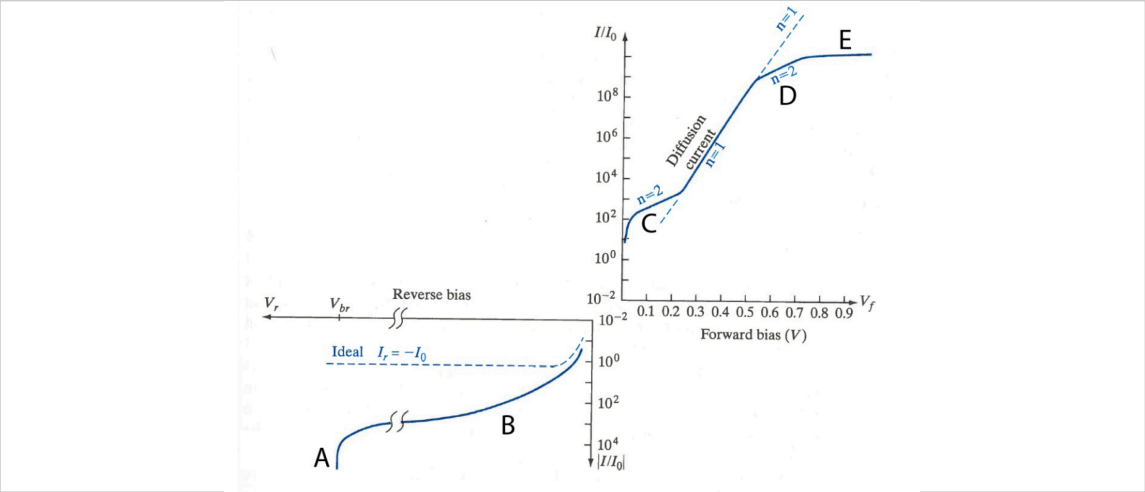
Majority carrier mobility: [ ] $\text{cm}^2/(\text{V} \cdot \text{s})$

(correct: 4p, wrong: 0p, blank: 0p, minimum score 0p)

You may attach calculations if you wish.

Maximum marks: 8

5



The illustration above highlights the most important differences in the I-V characteristics of an ideal pn-junction and a real pn junction.

Fill in the blanks in the following section of text. Words are suggested for each blank – choose the most appropriate one. (correct: 1p, wrong: -1p, blank: 0p, minimum score: 0p)

In an ideal pn-junction the reverse saturation current is small and Select alternative (proportional to the voltage, voltage independent, grows quadratically with the voltage, diffusion dominated). For a real pn-junction this is not the case. In a real

junction, for a sufficiently large reverse bias reverse breakdown occurs (A). In a lightly doped junctions Select alternative (avalanche, Zener, Schottky, Shockley) breakdown is expected. This breakdown mechanism is characterized by

Select alternative (quantum mechanical tunneling, electrostatic discharge, impact ionization, Eddy currents) due to a

Select alternative (excess of carriers, short diffusion length, short length, large E-field) in the Select alternative

(transition point, contact potential, depletion region, neutral p side). Furthermore, due to Select alternative (scattering, electron-hole-pair generation, lack of carriers, quantum mechanical tunneling) in the depletion region, the reverse current will grow (B) also before breakdown is reached.

In forward bias, the current will grow exponentially for both the ideal and the real pn-junction for moderate forward bias.

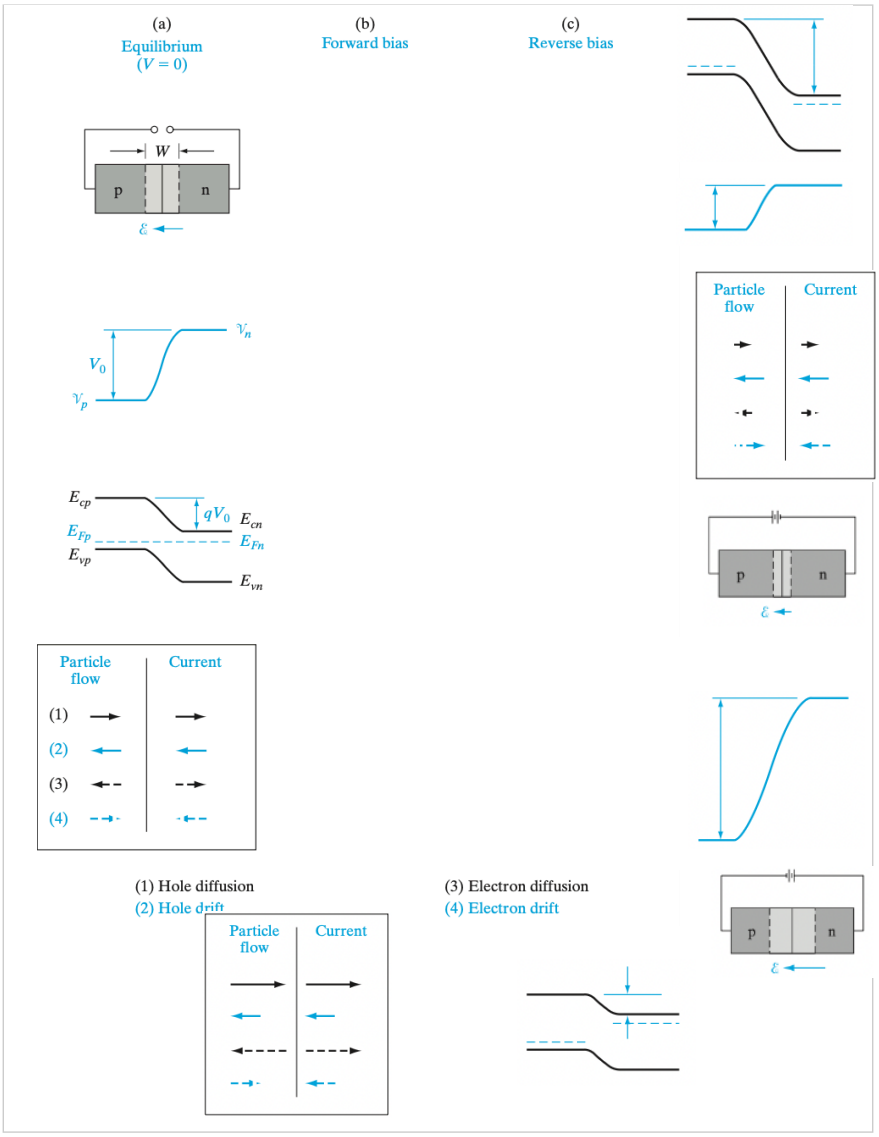
Although the initial growth (C) will be a little slower for the real junction due to Select alternative (recombination in the depletion region, reduced mobility, an activation potential at the junction, high resistance in the depletion region). For a

sufficiently large forward bias (D), the growth in forward current in the real junction will decrease as Select alternative (perfect bands, negligible drift, low-level injection, an abrupt junction) is no longer a good approximation and finally become

linear (E) as Select alternative (ohmic effects, minority effects, thermal effects, saturation effects) becomes dominant.

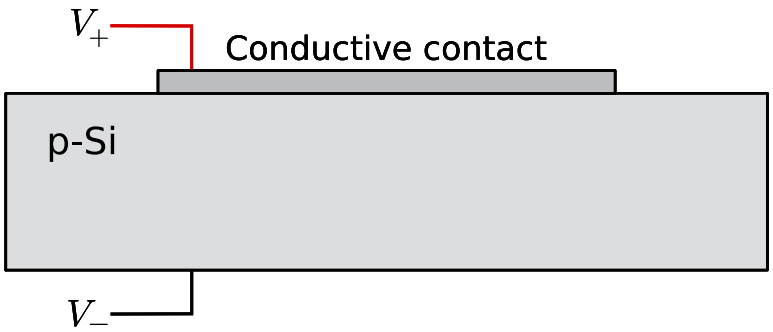
Maximum marks: 9

6 *Place the images in the correct positions. (correct: 0.5p, wrong: -1p, blank: -0p, minimum score: 0p)*



Maximum marks: 4

7



Anders is a researcher developing an electronic device at NTNU Nanolab. He wants to use a very thin conductive material as a contact on top of a p-doped Si substrate.

Being a careful researcher, he tests the resistance of the contacts before proceeding with his design by measuring the current after applying a small positive voltage over the contact and substrate.

To his surprise, he measures a *negative* current. Scratching his head, he measures the voltage over the contact and substrate in the configuration shown above, and finds a negative voltage of about 100mV. The magnitude of the voltage increases when he brings his work-lamp closer to the sample.[1]

(correct: 2p, wrong: -1p, blank: -1p, minimum score 0p)

What type of contact has Anders made?

Select alternative **(A rectifying PN-junction, A rectifying contact, An ohmic contact, None of the above).**

What can we say about the work function Φ of the conductive contact material relative to the p-Si substrate?

Select alternative (It is larger than the p-Si's work function, It is equal to the p-Si's work function, We cannot say anything about the relative sizes of the work functions, It is smaller than the p-Si's work function) .

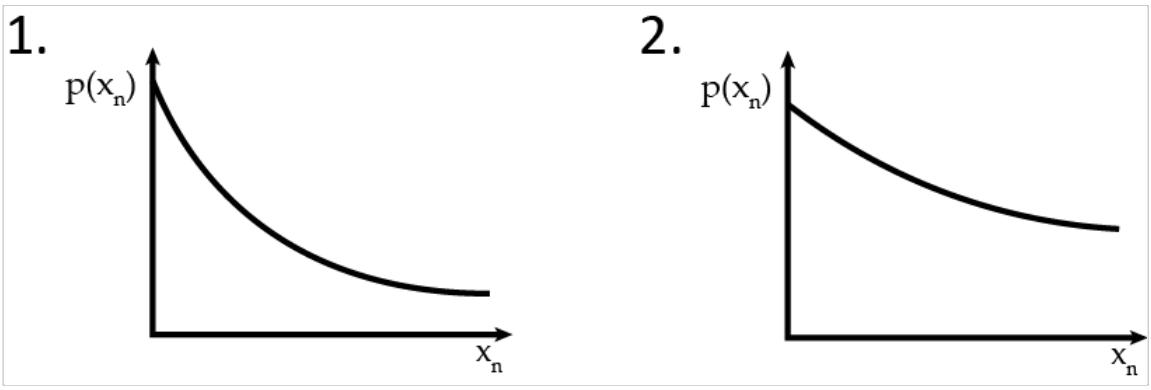
What sort of device has Anders accidentally made?

Select alternative **(All of the above, A photodiode, An ohmic metal-semiconductor contact, A Schottky diode solar cell, A PN-diode solar cell).**

[1] This is based on a true story from the lab.

Maximum marks: 6

8



The illustration shows the hole concentration on the n-side for two pn-junctions (device 1 and 2). Except for the doping levels we assume the two devices to be identical. Which of the following statements are correct ?
(correct: 2p, wrong: -2p, blank: 0p, minimum score 0p)
Select one or more alternatives

- ☐ The n-side doping concentration is highest in device 2
- ☐ In the figure we see a minority carrier distribution
- ☐ Both devices are currently under forward bias
- ☐ The n-side doping concentration is highest in device 1
- ☐ The hole current accross the junction is highest in device 2
- ☐ Both devices are currently in thermal equilibrium
- ☐ In the figure we see a majority carrier distribution

Maximum marks: 6

9 An abrupt Si junction has the following parameters:
$N_a = 10^{17}\ cm^{-3}$
$N_d = 10^{15}\ cm^{-3}$
$\epsilon_r = 11.8$

Calculate the Fermi level positions relative to the intrinsic Fermi level positions at 300 K in the p- and n-regions.
Answers:
(correct: 4p each, wrong: 0p, blank: 0p)

In p-region: $E_{ip} - E_F =$ ☐ eV

In n-region: $E_F - E_{in} =$ ☐ eV

Calculate the depletion region width, W.
(correct: 4p, wrong: 0p, blank: 0p)

Answer: ☐ μm

You may attach calculations if you wish.

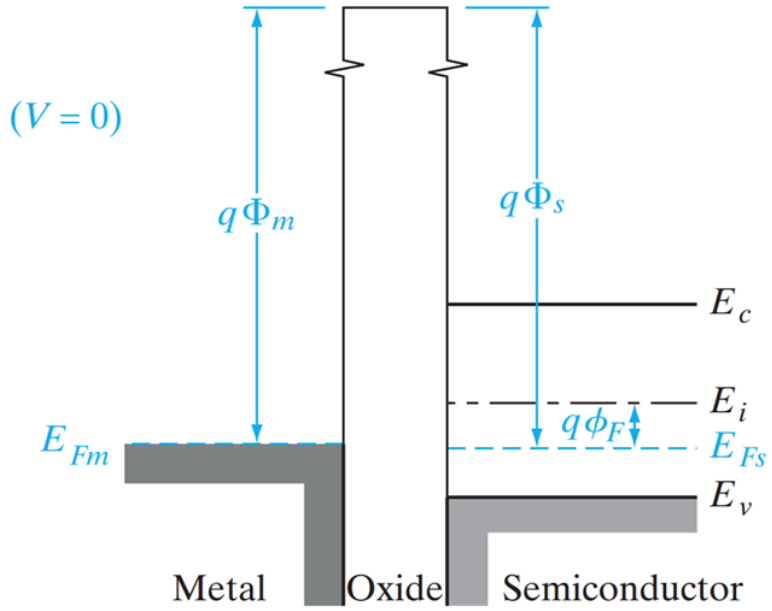
Maximum marks: 12

10 Consider a one-sided p+-n junction with a forward bias voltage $V_b >> \frac{kT}{q}$. What happens to the different current components if the bias voltage is increased by a factor 2?
(correct: 2p, wrong: -2p, blank: 0p, minimum score 0p)
Select one or more alternatives:

- [ ] The drift of holes and electrons remain approximately unchanged
- [ ] The diffusion of holes and electrons increase by a factor 2
- [ ] The diffusion of holes increase exponentially, the electron current remain unchanged
- [ ] The diffusion of holes and electrons increase exponentially
- [ ] The drift of holes increase by a factor 2 and the drift of electrons decrease by a factor 2.
- [ ] The drift of holes and electrons increase by a factor 2
- [ ] The diffusion of holes increase exponentially and the diffusion of electrons decrease exponentially.

Maximum marks: 4

11



Consider a MOS capacitor consisting of a metal whose work function is equal to that of a channel region consisting of Si doped with $2 \times 10^{17} \mathrm{cm}^{-3}$ of Boron. Recall that the intrinsic carrier concentration of Si is approximately given by $n_i = 1.5 \times 10^{10}\ \mathrm{cm}^{-3}$. Assume $T = 300K$.

a) Calculate the energy $q\phi_F =$ [ ] eV.

(correct: 4p, wrong: 0p, blank: 0p, minimum score 0p)

As the channel is brought into inversion, charges accumulate at the oxide-semiconductor interface. Si has a relative permittivity of $\epsilon_r = 11.8$

b) Calculate the depletion charge of the channel at strong inversion

$Q_d =$ [ ] $10^{-9}\ C/cm^2$

(correct: 4p, wrong: 0p, blank: 0p, minimum score 0p)

The gate oxide has a relative permittivity of $\epsilon_r = 3.9$ and has a thickness $d = 10\,\mathrm{nm}$. Assume no interface charges in the gate.

c) Find the threshold voltage for this MOS-channel

$V_T =$ [ ] V

(correct: 4p, wrong: 0p, blank: 0p, minimum score 0p)

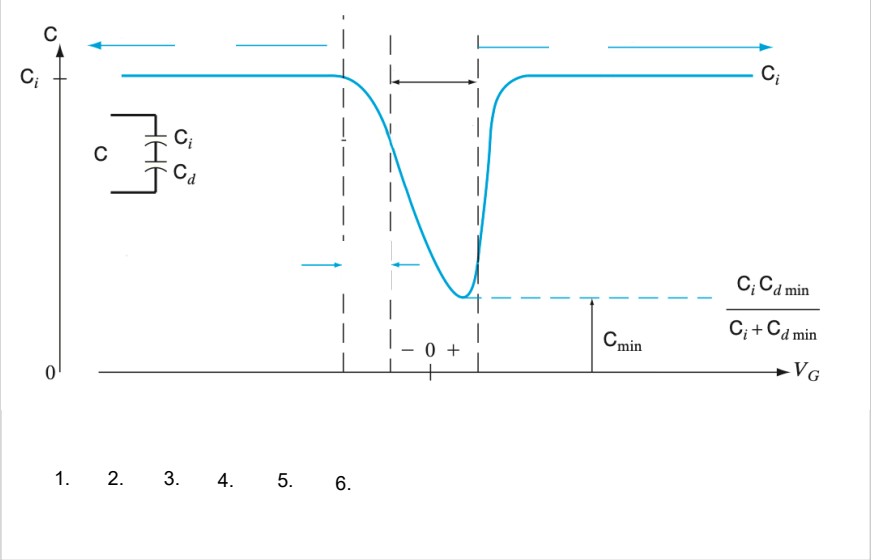
You may attach calculations if you wish.

Maximum marks: 12

12 *Place the labels in the correct positions. (correct: 1p, wrong: -1p, blank: 0p, minimum score: 0p)*

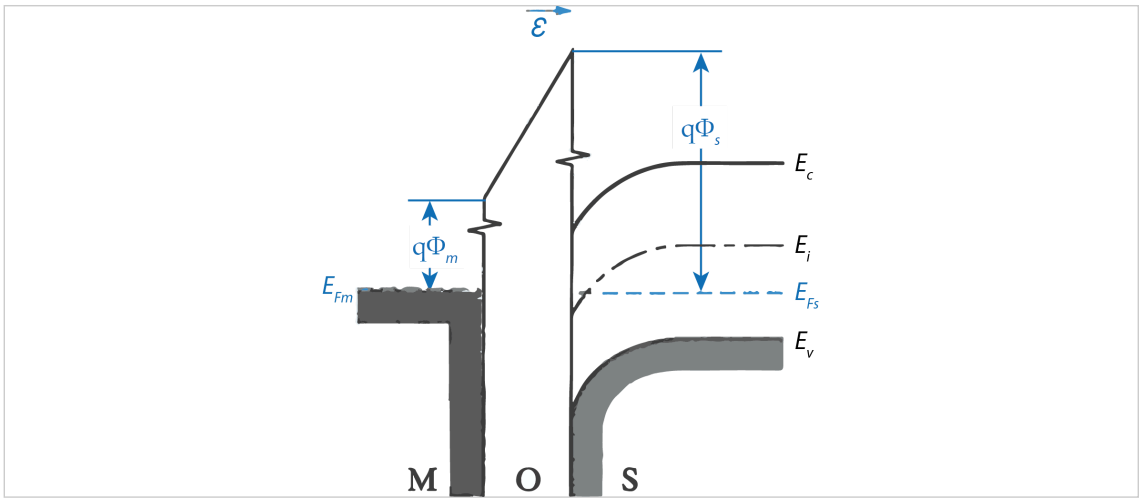
1. Strong inversion
2. Strong accumulation
3. Weak accumulation
4. Depletion and weak inversion
5. V_{FB}
6. V_T

Place the labels in the correct positions:



Maximum marks: 6

13



The illustration shows the band diagram for a certain MOS capacitor. Which of the following statements are correct for this device?

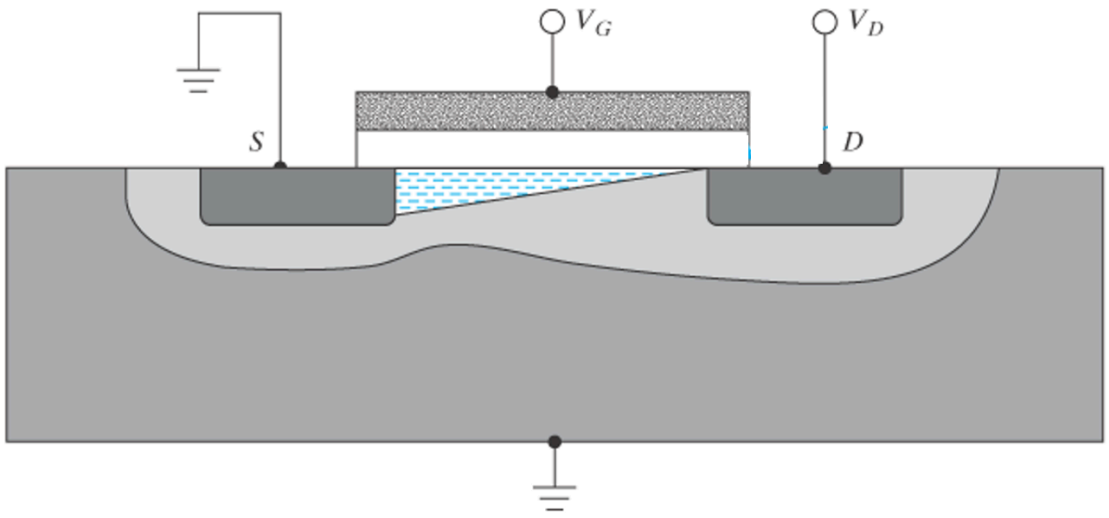
(correct: 2p, wrong: -2p, blank: 0p, minimum score 0p)

Select one or more alternatives

- [ ] To achieve flat band conditions we must apply a positive voltage across the MOS capacitor
- [ ] An inversion layer is currently present in the semiconductor
- [ ] The device is currently in strong inversion
- [ ] The semiconductor is doped with donor dopants
- [ ] The work functions in the metal and semiconductor are identical
- [ ] The MOS capacitor is currently in thermal equilibrium
- [ ] The work functions in the metal is larger than that of the semiconductor

Maximum marks: 4

14



The figure above shows the cross section of an enhancement mode (normally off) n-channel MOSFET at the onset of saturation.

Based on the indicated depletion region and inversion layer, select the correct voltage relationships.
(correct: 2p, wrong: -2p, blank: 0p, minimum score: 0p)
Select one or more alternatives:

- $V_G > V_T$
- $V_D \approx 0\text{V}$
- $V_G \approx 0\text{V}$
- $V_G < V_T$
- $V_D = V_G - V_T$

Maximum marks: 4

15 The threshold voltage of a MOSFET is given by

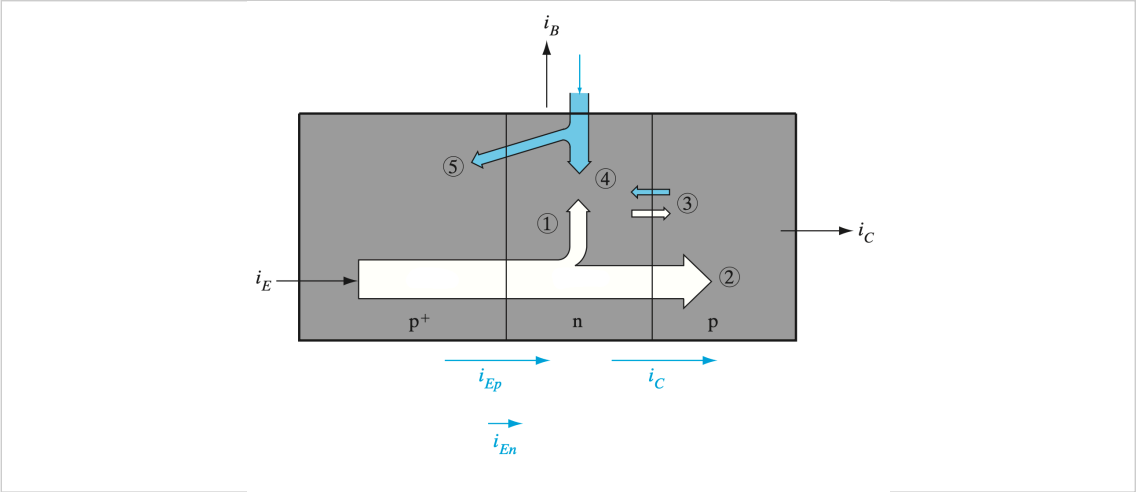
$$V_T = \Phi_{ms} - \frac{Q_i}{C_i} - \frac{Q_d}{C_i} + 2\phi_F \quad (1)$$

Which of the terms in (1) will depend on the doping concentration in the substrate?
(correct: 2p, wrong: -2p, blank: 0p, minimum score 0p)
Select one or more alternatives:

- $2\phi_F$
- $-\frac{Q_i}{C_i}$
- Φ_{ms}
- $-\frac{Q_d}{C_i}$

Maximum marks: 6

16



Fill in the blanks in the following section of text. Words are suggested for each blank – choose the most appropriate one. (correct: 1p, wrong: -1p, blank: 0p, minimum score: 0p)

The figure shows a p-n-p bipolar transistor, biased in the normal active mode, which is usually used for

Select alternative (rectification, power generation, switching, amplification).

To have a good p-n-p transistor, we would prefer that almost all the holes injected by the emitter are collected by the base.

The n-type base region should therefore be Select alternative (heavily doped, narrow, wide, positively charged), and the

hole lifetime should be Select alternative (long, short, equal to the electron lifetime).

A second requirement is that the current I_E crossing the emitter junction should be composed almost entirely of

Select alternative (holes, ions, electrons) injected to the base. This requirement is satisfied by Select alternative (doping the base region lightly compared with the emitter, doping the base region lightly compared with the collector, doping the base region heavily compared with the emitter, doping the base region heavily compared with the collector).

In the figure, the hole and electron flows in the p-n-p bipolar transistor are labeled from 1-6:

(1) injected holes Select alternative (lost to recombination, thermally generated, oscillating, scattering) in the base

(2) holes reaching the Select alternative (non, reverse, forward)-biased collector junction

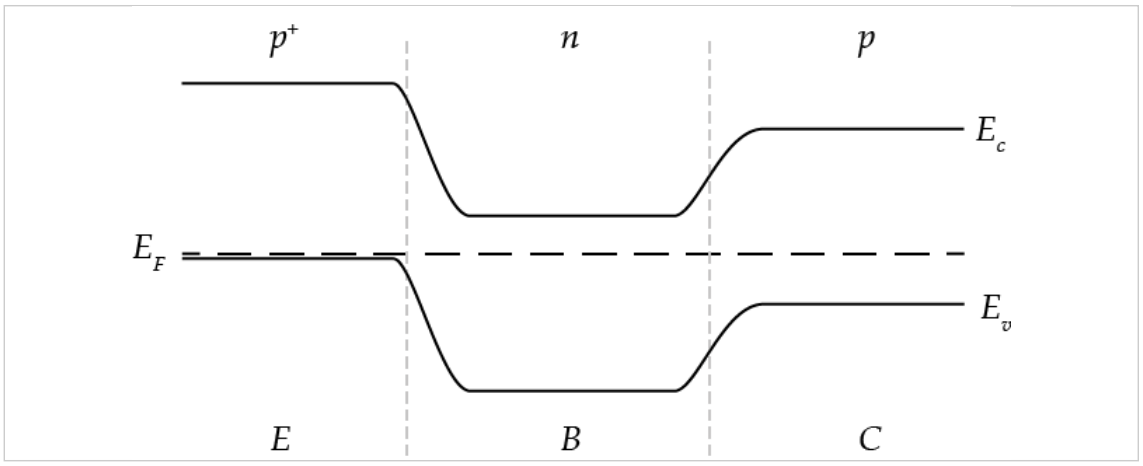
(3) thermally generated electrons and holes making up the Select alternative (base current, hole current, injection current, reverse saturation current) of the collector junction

(4) electrons supplied by the base contact for Select alternative (doping the base region, stimulated emission, thermal generation of charge carriers, recombination with holes)

(5) electrons injected across the Select alternative (forward, non, reverse)-biased emitter junction

Maximum marks: 10

17



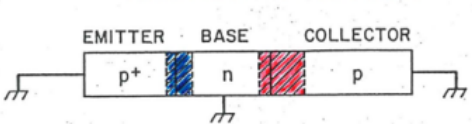
The illustration shows the simplified band diagram for a bipolar junction transistor (p-n-p). The emitter (E), base (B) and collector (C) regions are indicated. Which of the following statements are correct for the device with this band diagram?
(correct: 2p, wrong: -2p, blank: 0p, minimum score 0p)

Select one or more alternatives:

- [ ] There is currently a reverse bias across the B-C junction
- [ ] The diffusion current across the E-B junction will be dominated by electrons
- [ ] The dopant concentration is higher in the emitter than in the collector
- [ ] The device is currently in thermal equilibrium
- [ ] The device is currently operated in the normal active mode

Maximum marks: 4

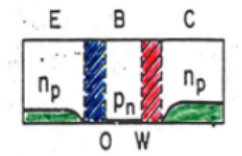
18

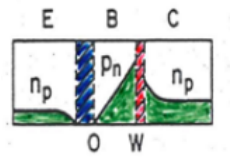


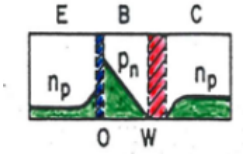
The figure above shows a p-n-p bipolar junction transistor in thermal equilibrium.
The figures below show the minority carrier distributions in the emitter (E), base (B), and collector (C), when the p-n-p transistor is operating in different regimes.

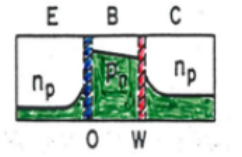
Match the figures and the names of the different operation regimes.
(correct: 1p, wrong: 0p, blank: 0p, minimum score 0p)

Please match the values:





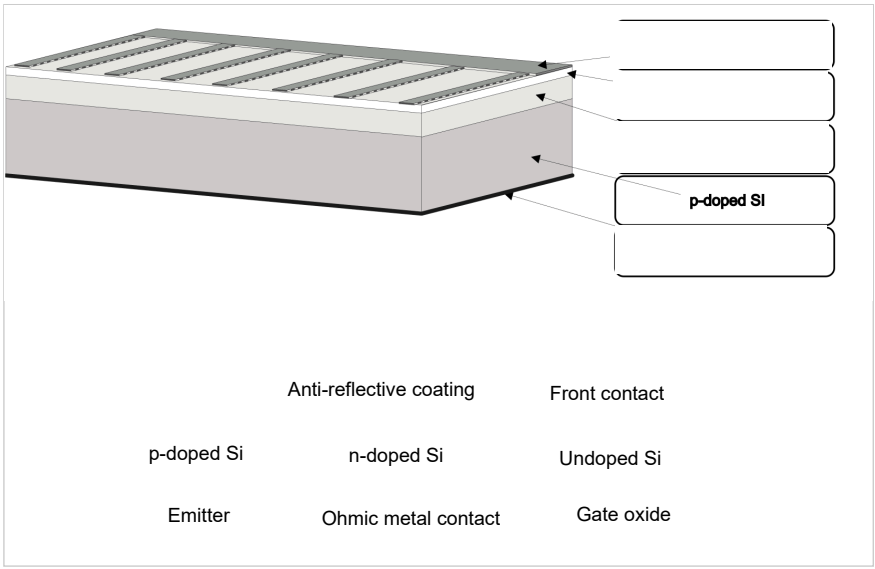




	Inverted	Cut-off	Saturation	Normal active
	○	○	○	○
	○	○	○	○
	○	○	○	○
	○	○	○	○

Maximum marks: 4

19 The schematic below shows a common solar cell setup. Place the correct descriptions to the corresponding labels below.



Maximum marks: 4

20

The p-n-p-n diode (25p)

Problem a-e gives 5p each.

Maximum marks: 25

ℹ Formulas

ℹ Constants and conversions

The p-n-p-n diode

The p-n-p-n diode is a four-layer semiconductor device with three junctions. We connect the diode to two terminals, A and K. The full diode is shown in Figure 1a. In the following you must make use of your knowledge about pn-junctions and BJTs to answer the questions about this device that you have probably not encountered before.

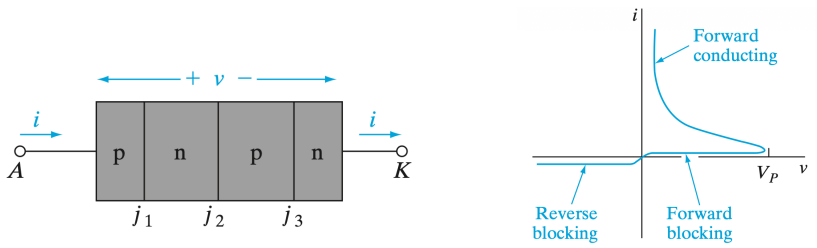


Figure 1: (a) The p-n-p-n diode. (b) I-V characteristics of the p-n-p-n diode.

(a) Sketch the depletion regions under (i) a small forward bias and (ii) reverse bias.

Under these biasing conditions, the diode is in the *forward-blocking* and *reverse-blocking* state, respectively.

(b) Explain why the current passing through the device is limited to a very small value under both of the biasing conditions in (a). Assume that no carriers diffuse across the n and p areas on each side of the j_2 junction.

When we apply a high enough voltage across the device (higher than the critical peak forward voltage V_p), the p-n-p-n diode switches to the *forward-conducting* state. We can then lower the voltage again, and the p-n-p-n diode will stay in the *forward-conducting state*, as shown in the I-V characteristic in Figure 1b. The device thus functions as a switch which is in the "off" state until switched by an external signal (a voltage pulse higher than V_p), and remains in the "on" state after switching.

To understand this behavior, we can model the p-n-p-n diode as two connected bipolar junction transistors, a p-n-p and an n-p-n, as shown in Figure 2, where j_1 and j_2 form the emitter and collector junctions in the p-n-p transistor and j_2 and j_3 form the collector and the emitter junctions of the n-p-n transistor. We see that the collector current of the p-n-p transistor drives the base of the n-p-n, and oppositely that the collector current of the n-p-n drives the base of the p-n-p.

(c) When we increase the forward bias over the whole p-n-p-n device, what do you expect will happen to the depletion region of j_2? With the first transistor (the p-n-p) in mind, how will this affect i_{C1}?

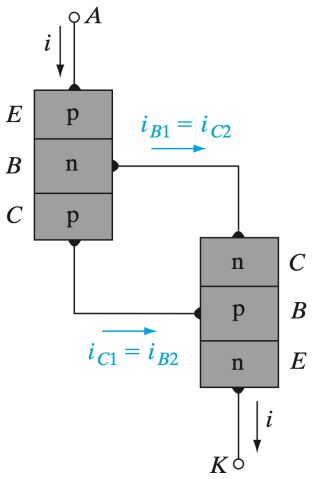


Figure 2: The two-transistor analogy of the p-n-p-n diode.

(d) How does the change in i_{C1} affect the second transistor (the n-p-n)? What do you expect will happen to the p-n-p-n device as a whole? *Hint: Note that the n-p-n transistor probably affects the p-n-p transistor as well!*

(e) Why does the switch stay in its "on" state even after we lower the device voltage to a small forward bias?

Formulas TFE-4146

SEMICONDUCTOR PHYSICS

Electron Momentum: $\mathrm{p} = m^*\mathrm{v} = \hbar\mathbf{k} = \dfrac{h}{\lambda}$ Planck: $E = h\nu = \hbar\omega$

Kinetic: $E = \dfrac{1}{2}m^*\mathrm{v}^2 = \dfrac{1}{2}\dfrac{\mathrm{p}^2}{m^*} = \dfrac{\hbar^2}{2m^*}\mathbf{k}^2$ (3-4) Effective mass: $m^* = \dfrac{\hbar^2}{d^2E/d\mathbf{k}^2}$ (3-3)

Total electron energy = $P.E. + K.E. = E_c + E(\mathbf{k})$

Fermi-Dirac e^- distribution: $f(E) = \dfrac{1}{e^{(E-E_F)/kT}+1} \cong e^{(E_F-E)/kT}$ for $E \gg E_F$ (3-10)

Equilibrium: $n_0 = \displaystyle\int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c-E_F)/kT}$ (3-15)

$N_c = 2\left(\dfrac{2\pi m_n^* kT}{h^2}\right)^{3/2}$ $N_v = 2\left(\dfrac{2\pi m_p^* kT}{h^2}\right)^{3/2}$ (3-16), (3-20)

$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_F-E_v)/kT}$ (3-19)

$n_i = N_c e^{-(E_c-E_i)/kT}$, $p_i = N_v e^{-(E_i-E_v)/kT}$ (3-21)

$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} = 2\left(\dfrac{2\pi kT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4}e^{-E_g/2kT}$ (3-23), (3-26)

Equilibrium: $n_0 = n_i e^{(E_F-E_i)/kT}$, $p_0 = n_i e^{(E_i-E_F)/kT}$ (3-25) $n_0 p_0 = n_i^2$ (3-24)

Steady state: $n = N_c e^{-(E_c-F_n)/kT} = n_i e^{(F_n-E_i)/kT}$, $p = N_v e^{-(F_p-E_v)/kT} = n_i e^{(E_i-F_p)/kT}$ (4-15) $np = n_i^2 e^{(F_n-F_p)/kT}$ (5-38)

$\mathscr{E}(x) = -\dfrac{d\mathscr{V}(x)}{dx} = \dfrac{1}{q}\dfrac{dE_i}{dx}$ (4-26)

Poisson: $\dfrac{d\mathscr{E}(x)}{dx} = -\dfrac{d^2\mathscr{V}(x)}{dx^2} = \dfrac{\rho(x)}{\epsilon} = \dfrac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$ (5-14)

$\mu \equiv \dfrac{q\bar{t}}{m^*}$ (3-40a) Drift: $\mathrm{v}_d \cong \dfrac{\mu\mathscr{E}}{1 + \mu\mathscr{E}/\mathrm{v}_s}\begin{cases} = \mu\mathscr{E} \text{ (low fields, ohmic)} \\ = \mathrm{v}_s \text{ (high fields, saturated vel.)} \end{cases}$ (Fig. 6-9)

Drift current density: $\dfrac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$ (3-43)

$$J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx}$$

Conduction Current: drift diffusion (4–23)

$$J_p(x) = q\mu_p p(x)\mathscr{E}(x) - qD_p \frac{dp(x)}{dx}$$

$$J_{\text{total}} = J_{\text{conduction}} + J_{\text{displacement}} = J_n + J_p + C\frac{dV}{dt}$$

Continuity: $\frac{\partial p(x,t)}{\partial t} = \frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p}$ $\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_n}$ (4–31)

For steady state diffusion: $\frac{d^2\delta n}{dx^2} = \frac{\delta n}{D_n\tau_n} \equiv \frac{\delta n}{L_n^2}$ $\frac{d^2\delta p}{dx^2} = \frac{\delta p}{L_p^2}$ (4–34)

Diffusion length: $L \equiv \sqrt{D\tau}$ Einstein relation: $\frac{D}{\mu} = \frac{kT}{q}$ (4–29)

p-n JUNCTIONS

Equilibrium: $V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} = \frac{\text{kT}}{\text{q}}\ln\frac{N_a}{n_i^2/N_d} = \frac{\text{kT}}{\text{q}}\ln\frac{N_aN_d}{n_i^2}$ (5–8)

$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT}$ (5–10) $W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)\right]^{1/2}$ (5–57)

One-sided abrupt p^+-n: $x_{n0} = \frac{WN_a}{N_a + N_d} \simeq W$ (5–23) $V_0 = \frac{qN_dW^2}{2\epsilon}$

$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1)$ (5–29)

$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p}$ (5–31b)

Ideal diode: $I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$ (5–36)

Non-ideal: $I = I_0'(e^{qV/\mathfrak{n}kT} - 1)$ ($\mathfrak{n}$ = 1 to 2) (5–74)

With light: $I_{\text{op}} = qAg_{\text{op}}(L_p + L_n + W)$ (8–1)

$$I_D = \frac{\bar{\mu}_n Z C_i}{L}\left\{(V_G - V_{FB} - 2\phi_F - \tfrac{1}{2}V_D)V_D - \frac{2}{3}\frac{\sqrt{2\epsilon_s q N_a}}{C_i}[(V_D + 2\phi_F)^{3/2} - (2\phi_F)^{3/2}]\right\} \quad (6\text{-}50)$$

$$I_D \simeq \frac{\bar{\mu}_n Z C_i}{L}[(V_G - V_T)V_D - \tfrac{1}{2}V_D^2] \quad (6\text{-}49)$$

Saturation: $I_D(\text{sat.}) \simeq \frac{1}{2}\bar{\mu}_n C_i \frac{Z}{L}(V_G - V_T)^2 = \frac{Z}{2L}\bar{\mu}_n C_i V_D^2(\text{sat.}) \quad (6\text{-}53)$

$$g_m = \frac{\partial I_D}{\partial V_G} \quad ; \quad g_m(\text{sat.}) = \frac{\partial I_D(\text{sat.})}{\partial V_G} \simeq \frac{Z}{L}\bar{\mu}_n C_i(V_G - V_T) \quad (6\text{-}54)$$

For short L: $I_D \simeq Z C_i(V_G - V_T)v_s \quad (6\text{-}60)$

Subthreshold slope: $S = \frac{dV_G}{d(\log I_D)} = \frac{kT}{q}\ln 10\left[1 + \frac{C_d + C_{it}}{C_i}\right] \quad (6\text{-}66)$

BJT-p-n-p

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right) \quad (7\text{-}18) \qquad \begin{aligned}\Delta p_E &= p_n(e^{qV_{EB}/kT} - 1)\\ \Delta p_C &= p_n(e^{qV_{CB}/kT} - 1)\end{aligned} \quad (7\text{-}8)$$

$$I_C = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{csch}\frac{W_b}{L_p} - \Delta p_C \operatorname{ctnh}\frac{W_b}{L_p}\right)$$

$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_b}{2L_p}\right] \quad (7\text{-}19)$$

$$B = \frac{I_C}{I_{Ep}} = \frac{\operatorname{csch} W_b/L_p}{\operatorname{ctnh} W_b/L_p} = \operatorname{sech}\frac{W_b}{L_p} \simeq 1 - \left(\frac{W_b^2}{2L_p^2}\right) \quad (7\text{-}26)$$

(Base transport factor)

$$\gamma = \frac{I_{Ep}}{I_{En} + I_{Ep}} = \left[1 + \frac{L_p^n n_n \mu_n^p}{L_n^p p_p \mu_p^n}\tanh\frac{W_b}{L_p^n}\right]^{-1} \simeq \left[1 + \frac{W_b n_n \mu_n^p}{L_n^p p_p \mu_p^n}\right]^{-1} \quad (7\text{-}25)$$

(Emitter injection efficiency)

$$\frac{i_C}{i_E} = B\gamma \equiv \alpha \quad (7\text{-}3) \qquad \frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta \quad (7\text{-}6) \qquad \frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t} \quad (7\text{-}7)$$

(Common base gain) (Common emitter gain) (For $\gamma = 1$)

Capacitance: $C = \left|\frac{dQ}{dV}\right|$ (5-55)

Junction Depletion: $C_j = \epsilon A\left[\frac{q}{2\epsilon(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2} = \frac{\epsilon A}{W}$ (5-62)

Stored charge exp. hole dist.: $Q_p = qA\int_0^\infty \delta p(x_n)dx_n = qA\Delta p_n\int_0^\infty e^{-x_n/L_p}dx_n = qAL_p\Delta p_n$ (5-39)

$I_p(x_n = 0) = \frac{Q_p}{\tau_p} = qA\frac{L_p}{\tau_p}\Delta p_n = qA\frac{D_p}{L_p}p_n(e^{qV/kT} - 1)$ (5-40)

$G_s = \frac{dI}{dV} = \frac{qAL_p p_n}{\tau_p}\frac{d}{dV}(e^{qV/kT}) = \frac{q}{kT}I$ (5-67c)

Long p^+-n: $i(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt}$ (5-47)

MOS-n CHANNEL

Oxide: $C_i = \frac{\epsilon_i}{d}$ Depletion: $C_d = \frac{\epsilon_s}{W}$ MOS: $C = \frac{C_i C_d}{C_i + C_d}$ (6-36)

Threshold: $V_T = \underbrace{\Phi_{ms} - \frac{Q_i}{C_i}}_{\text{Flat band}} - \frac{Q_d}{C_i} + 2\phi_F$ (6-38)

Inversion: $\phi_s\,(\text{inv.}) = 2\phi_F = 2\frac{kT}{q}\ln\frac{N_a}{n_i}$ (6-15) $W = \left[\frac{2\epsilon_s\phi_s}{qN_a}\right]^{1/2}$ (6-30)

$Q_d = -qN_aW_m = -2(\epsilon_s qN_a\phi_F)^{1/2}$ (6-32) At V_{FB}: $C_{FB} = \frac{C_i C_{\text{debye}}}{C_i + C_{\text{debye}}}$

Debye screening length: $L_D = \sqrt{\frac{\epsilon_s kT}{q^2 p_0}}$ (6-25) $C_{\text{debye}} = \frac{\epsilon_s}{L_D}$ (6-40)

Substrate bias: $\Delta V_T \simeq \frac{\sqrt{2\epsilon_s qN_a}}{C_i}(-V_B)^{1/2}$ (n channel) (6-63)

Physical Constants and Conversion Factors for the Exam in TFE-4146

Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K
	$= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.60 \times 10^{-19}$ C
Electronic rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm
	$= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.63 \times 10^{-34}$ J-s
	$= 4.14 \times 10^{-15}$ eV-s
Room temperature value of kT	$kT = 0.0259$ eV
Speed of light	$c = 2.998 \times 10^{10}$ cm/s

1 Å (angstrom) $= 10^{-8}$ cm	
1 μm (micron) $= 10^{-4}$ cm	
1 nm = 10 Å $= 10^{-7}$ cm	
2.54 cm = 1 in.	
1 eV $= 1.6 \times 10^{-19}$ J	

Prefixes:

milli-,	m-	$= 10^{-3}$
micro-,	μ-	$= 10^{-6}$
nano-,	n-	$= 10^{-9}$
pico-,	p-	$= 10^{-12}$
kilo-,	k-	$= 10^{3}$
mega-,	M-	$= 10^{6}$
giga-,	G-	$= 10^{9}$

A wavelength λ of 1 μm corresponds to a photon energy of 1.24 eV.