

EE2800 Assignment 4

Due: 9:00 AM, Apr. 30, 2024

1. Consider a clean abrupt metal-semiconductor contact between n-type Si and gold. The Fermi level of the semiconductor is located 0.3 eV below conduction band edge, the electron affinity of Si is 4.05 V, whereas the work function of gold Φ_m is 4.8 V. At 300 K Si has a band gap of 1.12 eV. (18 marks)
 - a. What is the work function Φ_s of this n-type Si? (4 marks)
 - b. Sketch the band diagrams of the metal and semiconductor before and after contact. Does this form a Schottky barrier or an Ohmic contact? If it is a Schottky barrier, what is the contact potential? (8 marks)
 - c. If instead, considering a p-type Si where the Fermi level is located 0.3 eV above valence band edge and the interface states pin the surface Fermi level 0.8 eV above valence band edge, sketch the band diagram of the semiconductor after contact. Does this form a Schottky barrier or an Ohmic contact? If it is a Schottky barrier, what is the contact potential? (6 marks)
2. In class, we have extensively discussed the current and carrier flow in a p-n-p bipolar junction transistor (BJT) as shown the below Fig. 1. Redraw Fig. 1 for an n-p-n BJT with clear labels of carrier and current flow and their directions, and explain the five major current flow components (①-⑤). (15 marks)

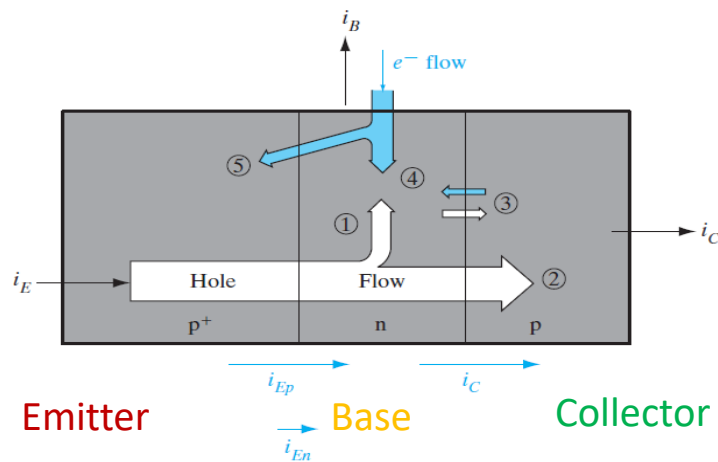


Figure 1. Current and carrier flow in a p-n-p BJT

3. In class, we have derived the hole distribution in the base region of a p-n-p BJT and the terminal currents. Here let's try to repeat the derivations for an n-p-n BJT. (20 marks)

(Optional bonus question: mark will be counted but the total mark of this assignment will not exceed 100)

- Redraw Fig. 2 for the case of an n-p-n BJT in normal active mode, with clear labels of the relevant minority carriers in each region. Write down the expressions for excess electron concentrations at the two boundaries of the base region, *i.e.* Δn_E and Δn_C . (3 marks)
- Write down the diffusion equation for electrons (δn) in the base region, its general solution, and the boundary conditions. Please clearly define the coordinate system before writing down the equations. (3 marks)
- Solve for the constants in the general solution and write down the full solution for electron distribution in base. (3 marks)
- The electron diffusion current in the base should be given by $I_n(x_p) = qAD_n \frac{d\delta n(x_p)}{dx_p}$. Calculate the emitter electron current I_{En} and collector current I_C . By applying proper approximations, write down the approximated I_{En} and I_C . (3 marks)
- By subtracting I_C from I_{En} , write down the expression for base recombination current with proper approximation. (2 marks)
- Write down the expression for hole diffusion current in the emitter junction (I_{Ep}), then write down the full expression for base current I_B . (2 marks)
- Ignoring the contribution from Δn_C , write down the expressions for emitter injection efficiency γ , base transport factor B , current transport ratio α , and base-to-collector amplification factor β . Your final expressions should only contain material and structural parameters like $D_{n/p}$, $L_{n/p}$, n_p/p_n , $\tau_{n/p}$. (4 marks)

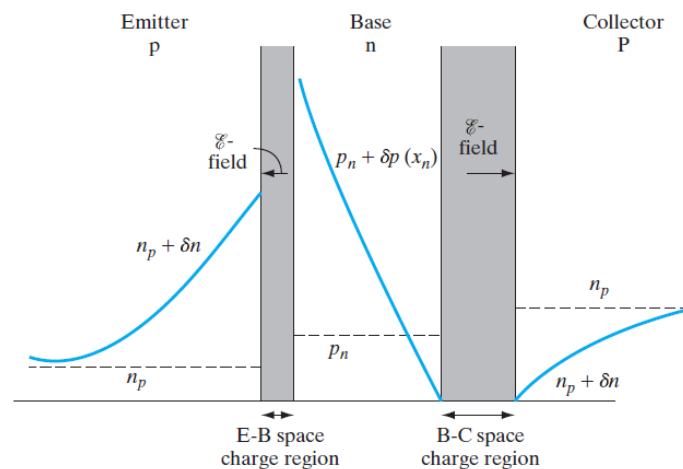


Figure 2. Minority carrier distribution in a p-n-p BJT in normal active mode.

4. A p-n-p bipolar junction transistor at 300 K has an area of 1 cm^2 and a base width $W_b = 1 \text{ } \mu\text{m}$. The doping concentrations of emitter and base regions are $N_A = 10^{17} \text{ cm}^{-3}$ and $N_D = 10^{15} \text{ cm}^{-3}$ respectively. The intrinsic carrier concentration is $1.5 \times 10^{10} \text{ cm}^{-3}$. The transistor is biased using the common-emitter circuit shown in Fig. 3. The mobilities and recombination lifetime of electrons and holes at 300 K are given in the below table. In this question, we assume Δp_C is negligible compared with Δp_E . (23 marks)

	Mobility	Recombination lifetime τ
Electron	$1450 \text{ cm}^2/(\text{V}\cdot\text{s})$	$0.1 \text{ } \mu\text{s}$
Hole	$500 \text{ cm}^2/(\text{V}\cdot\text{s})$	$10 \text{ } \mu\text{s}$

- Calculate the diffusivities, D_n and D_p , as well as diffusion lengths, L_n and L_p , for electrons and holes, respectively. (6 marks)
- Assuming the voltage drop V_{BE} is small, calculate the base current I_B , then calculate the actual forward bias V_{EB} . (6 marks)
- Calculate the emitter injection efficiency γ , base transport factor B , current transfer ratio α , and base-to-collector amplification factor β . (8 marks)
- Calculate the collector current I_C and voltage drop V_{CE} . From your results, find out the operation mode (cut-off, normal active, or saturation) of this BJT. Provide reasoning for your conclusion. (5 marks)

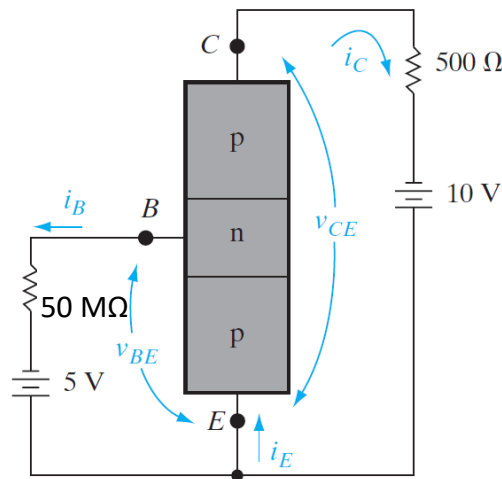


Figure 3. Minority carrier distribution in a p-n-p BJT in normal active mode.

- In class, we have discussed the charge distribution of an n-MOSFET in the inversion region under depletion approximation, as shown in Fig. 4. In a similar style as Fig. 4, sketch the qualitative charge distribution of this n-MOSFET in the accumulation and depletion

regions. In your sketch, please be mindful of the signs of relevant charges. Clearly label and explain the different charge contributions (e.g. in Fig. 4 Q_n refers to inversion layer charge). (10 marks)

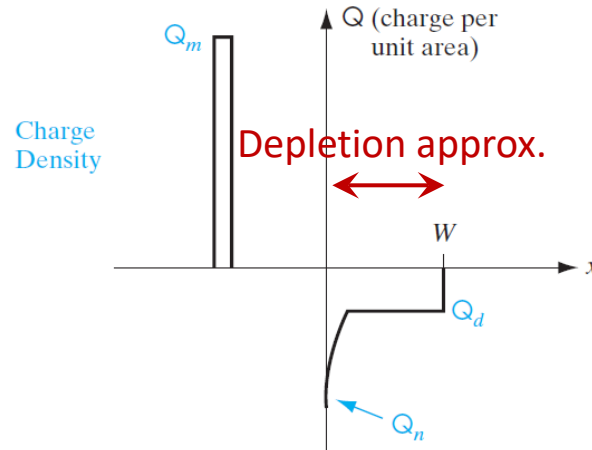


Figure 4. Charge distribution of an n-MOSFET in the inversion region.

6. An n-MOSFET features a p-type Si substrate (channel) with $N_A = 5 \times 10^{15} \text{ cm}^{-3}$. The intrinsic carrier concentration is $1.5 \times 10^{10} \text{ cm}^{-3}$. The insulator thickness is $100 \text{ \AA}$ with a relative dielectric constant of 3.9. The relative dielectric constant of Si is 11.8. (32 marks)
 - a. Calculate ϕ_F and the surface potential at the onset of strong inversion (threshold), i.e. $\phi_s(\text{inv.})$. (6 marks)
 - b. Considering the surface potential pinning effect, calculate the approximate values of voltage dropped on the insulator, i.e. V_i , when the gate voltage V_G is 5 V and -5 V , respectively. (4 marks)
 - c. At the onset of strong inversion, calculate the maximum depletion region width, W_m , under depletion approximation. Then calculate the total depletion region charge, Q_d . (6 marks)
 - d. Calculate the insulator capacitance per unit area, C_i . (4 marks)
 - e. Calculate the threshold voltage of this n-MOSFET. (4 marks)
 - f. Calculate the depletion layer capacitance at W_m , C_d . (4 marks)
 - g. Calculate the minimum capacitance of this n-MOSFET, $C_{\min}$. (4 marks)