
EE566 Solid State Devices

Spring 2006
Dept of Electrical Engineering
University of Notre Dame
Instructor: Debdeep Jena (djena@nd.edu, x8835)

Assignment 7

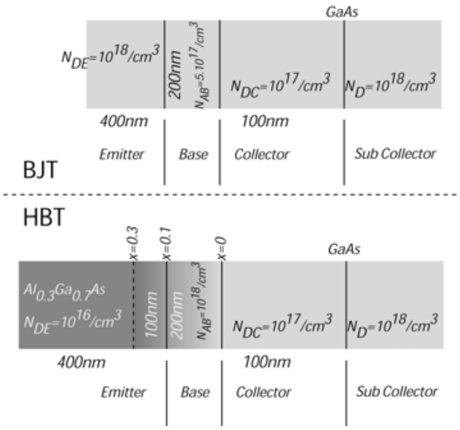
Posted: 03/31/2006
Due: 04/07/2006

Reading
Chapter 6 of Textbook. Especially interesting sections are 6.5.2 and 6.7, and Figs 6.11 & Fig 6.24.

Problem 1 (Practice Problem on BJTs)
Problem 6.17, **Attached Figures**.

Problem 2 (Follow up on Problem 1 - BJT in a radiation environment)
Problem 6.18, **Attached Figures**.

Problem 3 (**Homojunction vs Heterojunction Bipolar Transistors**)



Consider the GaAs-based n-p-n BJT and HBT shown in the figure (not to scale!). The BJT is made of GaAs, whereas the base of the HBT is linearly graded from $Al_{0.10}Ga_{0.90}As$ at the emitter end to $GaAs$ at the collector end. The emitter material of the HBT is $Al_{0.3}Ga_{0.7}As$ linearly graded to $Al_{0.1}Ga_{0.9}As$ at the base end. All lengths in the diagram below are the TOTAL layer thicknesses. For most calculations, you will need to subtract the depletion thicknesses. Refer to Kroemer's paper (pg 76-78, handouts) for this problem. Use constants for GaAs at 300K.

a) Sketch the detailed band diagram and the Electric field of the BJT and HBT in equilibrium. What is the purpose of the heavily doped sub-collector? What is the quasi-electric field E_B in the base of the HBT? Calculate, and then verify both with 1D Poisson.
b) Solve the drift-diffusion equation in the base to obtain an expression for the minority carrier concentration in the base $n_B(x)$ in terms of E_B, collector current J_C, and *effective* base width W_B.
c) Obtain an analytical expression, and calculate the numerical value for the base transit time τ_{tr} in both the BJT and the HBT. What is the ratio? Make reasonable approximations.
d) Find the emitter injection efficiency γ_E and the base transport factor α_T for the BJT and HBT. What is the ideal gain β_F at V_{BE}=0.8 volt? What is the improvement in the HBT?
e) What are the pros and cons of each (BJT vs. HBT)? Compare in tabular form.
f) With the help of the web, investigate the current interest in SiGe-based HBTs, and comment on how HBT ideas have resulted in a massive drive towards BiCMOS technology. Who are the major players in the field? What are the applications for Si-based HBTs? Write a paragraph summarizing your findings.

Problem 4 (BJT with recombination in the base)
Problem 6.19, **Attached Figures**.

Problem 5 (Polysilicon Emitters)
Problem 6.30, **Textbook**.

Problem 6 (Effect of Base resistance)
Problem 6.36, **Textbook.**

6.5* (a) Find Q_{BO}, the base-majority charge in the quasi-neutral region for the transistor data plotted in Figure 6.4.

(b) Find the base width x_B if the average base doping is 10^{17} atoms cm^{-3}. (Assume that $\tilde{D}_n = 25$ cm^2 s^{-1}.)

6.6† Use approximation techniques to determine the net number of dopant atoms per unit area between the base-emitter junction plane and the base-collector junction plane in the switching transistor of Figure 6.15 and the amplifying transistor of Figure 6.16. Compare these values with the dopant atoms per unit area in the quasi-neutral base (Gummel Number in Equation 6.2.3) for the transistor of Problem 6.5 and explain any differences between the results.

6.7 Redo the problem considered in the example of Sec. 6.3 if both the base-emitter and base-collector junctions are linearly graded with the grading coefficient $a = 10^{22}$ cm^{-4} (where $N_d - N_a = ax$), and $\phi_i = 0.872$ V.

6.8* The accompanying table gives values of the net dopant density ($N_d - N_a$) as a function of position relative to the junction plane between the emitter and base on a transistor with the doping profile of Figure 6.16.

Net dopant density ($N_d - N_a$) (cm^{-3})	**Distance from base-emitter junction (μm)**
7.36×10^{17}	-0.125
-1.25×10^{16}	$+0.045$
-4.0×10^{16}	$+0.115$
-1.9×10^{16}	$+0.15$
-6.4×10^{15}	$+0.205$
-1.5×10^{15}	$+0.250$

Assume that the transistor has an active area of 2×10^{-6} cm^2. (a) Plot these values on a linear scale and argue that the profile can be roughly approximated by a one-sided step junction having $N_a \approx 2 \times 10^{16}$ cm^{-3}. (b) Make a plot similar to that of Figure 6.11 to show Q_{VE} versus total voltage for the junction over the bias range from breakdown to $+0.3$ V. Find values for ϕ_i and K_A as shown in Figure 6.11.

6.9 Use the result of Problem 6.1 and the data of Problem 6.8 to estimate the size of the field in the quasi-neutral base of the transistor having the doping profile sketched in Figure 6.16.

6.10 Draw an equivalent circuit similar to Figure 6.12 and write equations similar to Equations 6.4.9 and 6.4.10 to represent the Ebers–Moll model for a *pnp* transistor.

6.11 Show that Figure 6.14*b* represents the Ebers–Moll model for a transistor driven by base current.

6.12* Derive Equation 6.4.17 for the voltage drop across a saturated transistor as predicted by the Ebers-Moll model. Evaluate $V_{CE\,\mathrm{sat}}$ for $I_C/I_B = 10$, $\alpha_F = 0.985$, and $\alpha_R = 0.72$.

6.13 Use the Ebers–Moll equations for a *pnp* transistor (Problem 6.10) to find the ratio of the two currents I_{CE0} to I_{CB0} where I_{CE0} is the current flowing in the reverse-biased collector with the base open circuited, and I_{CB0} is the current flowing in the reverse-biased collector with the emitter open circuited. Explain the cause for the difference in the currents in terms of the physical behavior of the transistor in the two situations.

6.14† Consider an *npn* transistor that is biased in the active mode. At time $t = 0$, an intense visible light is focused on the collector-base space-charge region. The light produces G hole-electron pairs per unit time inside the space-charge zone. (Consider that qG is roughly of the same order as the dc base current I_B.)

(a) If the emitter-base voltage and collector-base voltage are both held constant, what are the values of base, emitter, and collector currents for $t > 0$?

(b) Repeat part a if the base is driven by a current source so that the illumination does not alter I_B.

6.15 Near room temperature, the collector current I_C and the base current I_B are both normally positive for an *npn* transistor biased in the active mode. Assume that an *npn* transistor is under active bias and I_C is held constant while the temperature is increased. If we measure I_B, we find that its magnitude decreases and ultimately changes sign. What physical effects account for this behavior? (Consider all currents at the base lead.) [9]

6.16 Consider an *npn* transistor in which both the base and emitter regions are nonuniformly doped and in which recombination of reverse-injected holes into the emitter takes place at the emitter contact. Show that the emitter efficiency γ can be written as $\gamma = (1 + Q_{BO}\tilde{D}_{pE}/Q_{EO}\tilde{D}_{nB})^{-1}$ where Q_{EO} is the emitter dopant in the quasi-neutral region of the emitter, Q_{BO} is the base dopant in the quasi-neutral region of the base, and $\tilde{D}_{pE}$ and $\tilde{D}_{nB}$ are the effective minority-carrier diffusion coefficients in these regions. Show the consistency of this result with that given for the prototype transistor when it is subjected to the same recombination constraints (Equation 6.2.20).

6.17* An *npn* transistor has a cross-sectional area of 10^{-5} cm^2 and a quasi-neutral base that is uniformly doped with $N_a = 4 \times 10^{17}$ cm^{-3}, $D_{nB} = 18$ cm^2 s^{-1}, and $x_B = 0.5$ μm.

(a) If conditions in the emitter are similar to those described in Problem 6.16 and the emitter has total dopant (Q_{EO}/q) of 8×10^9 atoms and $\tilde{D}_{pE}$ is 2 $\text{cm}^2\ \text{s}^{-1}$, calculate γ.

(b) Estimate α_T, the transport factor if the base lifetime is 10^{-6} s.

(c) Calculate β_F for this transistor. What is the percentage error involved in taking $\beta_F \approx Q_{EO}\tilde{D}_{nB}/Q_{BO}\tilde{D}_{pE}$? This simplified form is sometimes used to estimate β_F.

6.18† Assume that the transistor of Problem 6.17 is placed in a radiation environment where the electron lifetime in the base decays according to the equation: $\tau_n = \tau_{n0} \exp -(t/t_d)$. In this equation t is measured in days and t_d is 10 days. Plot β_F as a function of time in days and determine the time interval until β_F drops to unity. What is the base lifetime when this occurs?

6.19† Consider the transistor structure shown in Figure P6.19.

(a) Derive an expression for the electron distribution in the base as a function of x assuming that recombination takes place. (This will demand solving an equation similar to Equation 5.3.10.)

(b) The slope of the distribution at $x = 0$ is proportional to the injected electron current, and the slope at $x = x_B$ is proportional to the collected electron current. The difference represents current lost because of recombination in the base (supplied by the base lead). Find an expression for this base recombination current as a function of L_n and x_B/L_n [$L_n = (D_n\tau_n)^{1/2}$].

(c) The dopant concentrations in the emitter, base, and collector are assumed to be uniform throughout each region with values of 10^{19}, 10^{17}, and $10^{15}\ \text{cm}^{-3}$, respectively. The hole lifetime in the emitter is 10^{-9} s and the electron lifetime in the base is 10^{-7} s. The emitter and base widths are each 1 μm. Calculate the emitter efficiency and β_F. Use Figure 1.16 to obtain values for the diffusion coefficients. [Hint: For this problem, it is best to express solutions for the continuity equation as the sum of the hyperbolic functions cosh (x/L_p) and sinh (x/L_p)].

6.20† By considering collector current as charge in transit ($I_C = qnv_dA$), use the known distribution of injected electrons in the base of an *npn* prototype transistor biased in the active mode to solve for the base transit time τ_B. That is, formulate the transit time as the integrated sum of incremental path lengths divided by velocity and then carry out the integration to prove that τ_B is given by $\tau_B = x_B^2/2D_n$ (i.e. take $\tau_B = \int_0^{x_B} dx/v$).

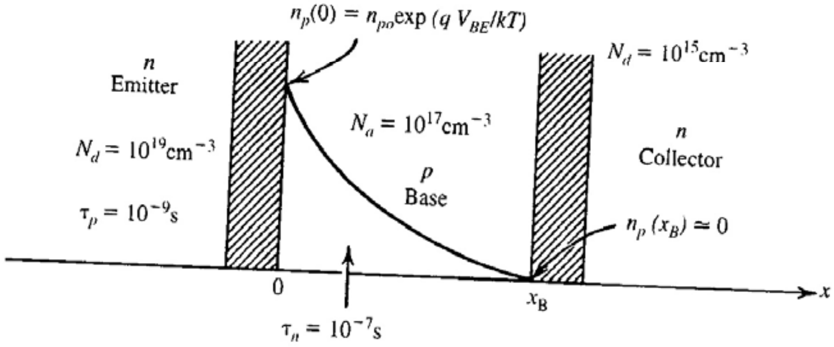


FIGURE P6.19

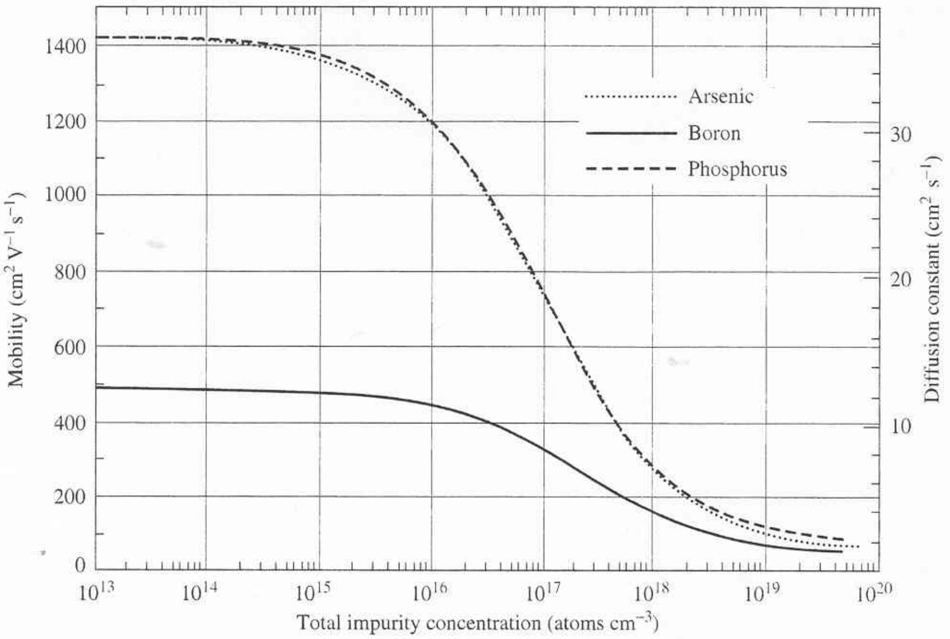


FIGURE 1.16 Electron and hole mobilities in silicon at 300 K as functions of the total dopant concentration. The values plotted are the results of curve fitting measurements from several sources. The mobility curves can be generated using Equation 1.2.10 with the following values of the parameters [3].

Parameter	***Arsenic***	***Phosphorus***	***Boron***
μ_{min}	52.2	68.5	44.9
μ_{max}	1417	1414	470.5
N_{ref}	9.68×10^{16}	9.20×10^{16}	2.23×10^{17}
α	0.680	0.711	0.719

An important practical consequence of the dependence of mobility on total impurity concentration is observed if a semiconductor is converted from one type to the other (p to n or n to p) by compensating the dopant impurity atoms already present. While the carrier densities depend on the difference between the concentrations of the two types of dopant impurities ($N_d - N_a$) (Equations 1.1.16 and 1.1.17), the scattering depends on the sum of the ionized impurity concentrations ($N_d + N_a$). Thus, the mobilities in a compensated semiconductor can be markedly lower than those in an uncompensated material with the same net carrier density.

The equation used in Figure 1.16 to represent the measured electron and hole mobilities in silicon is [3]

$$\mu = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + (N/N_{ref})^{\alpha}} \tag{1.2.10}$$

where N is the total dopant concentration in the silicon and the four parameters μ_{max}, μ_{min}, N_{ref}, and α have different values for each dopant species. Values of these parameters for the most common dopants in silicon are included in the caption for Figure 1.16. Table 1.1 gives numerical values of the mobility (as calculated from Equation 1.2.10) at decade values of N.

The dependence of electron mobility on dopant species is seen, from Figure 1.16, to be slight for total impurity concentrations less than 10^{19} cm^{-3}. In the high doping range (for $N > 10^{19}$ cm^{-3}), the mobility of phosphorus-doped silicon is 10 to 20% greater than