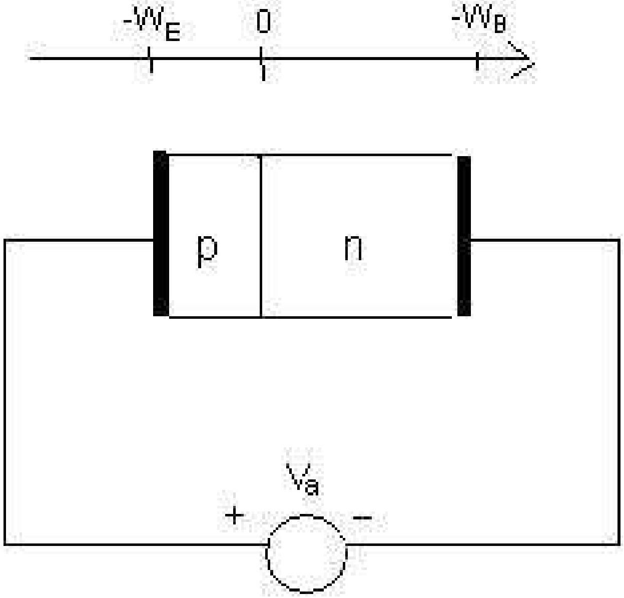
Final Examination EE 130
December 16, 1997
Time allotted: 180 minutes

**Problem 1: Semiconductor Fundamentals [30 points]**
A uniformly doped silicon sample of length 100$\mu$m and cross-sectional area 100$\mu$m$^2$ is maintained at 300K under equilibrium conditions. It has an acceptor density of $N_a = 10^1 6\text{cm}^{-3}$ and a hole concentration $p = 2.1 \times 10^4\text{cm}^{-3}$.

- **(a)** Determine the electron concentration, $n$. **[5 pts]**
- **(b)** Determine the donor density, $N_d$. **[5 pts]**
- **(c)** What is the mean scattering time for holes in this sample? **[5 pts]**
  Assume $m_h^* = 0.386 m_o$.
- **(d)** What is the resistance of this sample? **[5 pts]**
- **(e)** Draw the energy-band diagram, show the relative positions of $E_c$, $E_v$, $E_f$, and $_i$ for this sample at 600K. (Note: You should consider the increase in $n_i$ with temperature. Neglect the change of $E_g$ with temperature.) **[10 pts]**

**Problem 2: p-n Junction Diode [35 points]**

Consider the following silicon p-n step-junction diode maintained at 300K:



$N_a = 10^{17} cm^{-3}$ $N_d = 10^{15} cm^{-3}$ $\tau_n = 1\mu s$ $\tau_p = 1\mu s$ $W_E = 1\mu m$ $W_B = 500\mu m$ The cross-sectional area of the diode $A = 10^{-3}\text{cm}^2$.

**(a)** Determine the built-in potential, $\phi_i$. [**5 pts**]

**(b)** What is the reverse breakdown voltage, $BV$, of the diode? [**5 pts**]
Assume that the critical electric field for breakdown $E_1 = 3 \times 10^5$ V/cm.

**(c)** What is the capacitance of the diode at zero bias ($V_a = 0$ V)? [**5 pts**]

**(d)** What is the reverse saturation current, $I_o$, of the diode? [**10 pts**]

**(e)** What is the stored hole charge inside the diode, for $V_a = 0.5$ V? [**5 pts**]

**(f)** The limit of low-level injection is normally assumed to be when the minority-carrier density at the edge of the depletion region becomes equal to one tenth the majority-carrier density in that region. Determine the value of $V_a$ at which the limit of low-level injection is reached. [**5 pts**]

**Problem 3: Bipolar Junction Transistor [35 points]**

Consider an npn silicon BJT of area $A = 10^{-6} cm^2$ maintained at 300K and operating in the active region with $V_{BE} = 0.7V$ and $V_{CB} = 5V$, so that $x_B = 0.6 \mu m$:

Each region of the BJT is uniformly doped: $N_E = 10^{18} cm^{-3}$, $N_B = 10^{16} cm^{-3}$, $N_C = 10^{15} cm^{-3}$. The minority carrier diffusion constants are $D_E = 4cm^2/2$, $D_B = 30cm^2/s$, $D_C = 12cm^2/s$. The minority carrier lifetimes are $\tau_E = \tau_B = \tau_C = 10^{-6}$ s.

**(a)** What is the common emitter d.c current gain, $\beta_F$ , of this transistor? **[5 pts]**

**(b)** Sketch the energy-band diagram, indicating the positions of the Fermi levels in the quasi-neutral regions. **[10 pts]**

**(c)** What is the collector current, $I_C$? **[5 pts]**

**(d)** For what value of $V_{CB}$ will $I_C$ increase by 20%? **[10 pts]**

**(e)** Estimate the Early Voltage, $V_A$ . Hint: Use your result from part (d) and note that $V_A = I_C/g_0 = -x_B/(dx_B/dV_{CB})$. **[5 pts]**

**<u>Problem 4</u>: Metal-Oxide-Semiconductor Capacitor** [**25 points**] An $Al - SiO_2 - Si$ capacitor of area $A = 100\mu m^2$ has substrate doping $N_a = 10^{17} cm^{-3}$ and oxide thickness $x_{ox} = 100$ angstroms. The fixed charge density at the $Si - SiO_2$ interface $Q_f = 5 * 10^{10} q/cm^2$.

- **(a)** Calculate the flatband voltage, $V_{FB}$ [**5 pts**] ($q\Phi_M = 4.1eV; qX_{Si} = 4.05eV$)
- **(b)** Calculate the threshold voltage, $V_T$ [**5 pts**].
- **(c)** Sketch the low-frequency C-V curve for this capacitor, indicating the maximum and minimum capacitance values on your plot. [**5 pts**]
- **(d)** Sketch the equilibrium energy diagram of the MOS structure. Indicate the value of the band-bending, $qV_s$ in the silicon. [**10 pts**]

**Problem 5: MOS Field-Effect Transistor [45 points]**
A silicon n-channel MOSFET has $W = 10\mu m$, $L = 1\mu m$, and $x_{ox} = 100$ angstroms. At $V_{DS} = 0.1V$, the drain current is:
$I_D = 40\mu A$ at $V_G = 1.6V$, $I_D = 90\mu A$ at $V_G = 2.6V$

**(a)** Calculate the effective electron mobility. **[5 pts]** (Use the first-order model, i.e. the square law model)

**(b)** Calculate the threhold voltage, $V_T$ **[5 pts]**

**(c)** Without considering velocity saturation, what is $I_D$ at $V_{DS} = 5V$ and $V_G - V_T = 3V$? **[10 pts]**

**(d)** What is $I_D$ at $V_{DS} = 5V$ and $V_G - V_T = 3V$, with velocity saturation? **[5 pts]** (Assume that the critical electric field $E_C = 10^4 V/cm$

**(e)** Indicate in the table below (by checking the appropriate box for each line) the consequences of increasing the body doping, $N_a$, in an n-channel MOSFET. **[20 pts]**

| | increases | decreases | remains the same |
|---|---|---|---|
| Transconductance | | | |
| Body effect parameter,$\gamma$ | | | |
| Channel-length modulation parameter, $\lambda$ | | | |
| Subthreshold swing, S | | | |
| Drain-induced barrier lowering | | | |

**Problem 6: Metal-Semiconductor Contact [30 points]** A Schottky-barrier diode is made by depositing tungsten ($q\Phi_M = 4.5eV$) on n-type silicon.
T = 300 K
$N_d = 10^15cm^{-3}$
Area of the diode $A = 10\mu m^2$

**(a)** Determine the built-in potential, $\phi_i$ **[5 pts]**

**(b)** What is the equilibrium depletion width, $x_d(V_a = 0V)$? **[5 pts]**

**(c)** What is maximum electric field $E_{max}$, for $V_a = 0V$? **[5 pts]**

**(d)** Sketch the $V_a$ vs $1/C^2$ graph, label the x and y axis intercepts respectively. **[10 pts]**

**(e)** Can a Schottky-barrier diode be used in place of the pn emitter junction in a pnp BJT? Explain briefly.**[5 pts]**