6.012 Microelectronic Devices and Circuits
Spring 2005

April 20, 2005
Quiz #2

Problem #points

NAME________________________________________ 1___________

RECITATION TIME_________________________________ 2__________
3__________

Total________________

General guidelines (please read carefully before starting):

- Make sure to write your name on the space provided above.
- Open book: you can use any material you wish. But no computers.
- All answers should be given in the space provided. Please do not turn in any extra material.
- You have 120 minutes to complete the quiz.
- Make reasonable approximations and state them, i.e. low-level injection, extrinsic semiconductor, quasi-neutrality, etc.
- Partial credit will be given for setting up problems without calculations. NO credit will be given for answers without reasons.
- Use the symbols utilized in class for the various physical parameters, i.e. $N_n$, $\tau$, $\varepsilon$, etc.
- Pay attention to problems in which numerical answers are expected. An algebraic answer will not accrue full points. Every numerical answer must have the proper units next to it. Points will be subtracted for answers without units or with wrong units. In situations with a defined axis, the sign of the result is also part of the answer.

Unless otherwise stated, use:

\[ q = 1.6 \times 10^{-19} \text{ C} \]
\[ kT/q = 25 \text{ mV at room temperature} \]
\[ n_i = 10^{10} \text{ cm}^{-3} \text{ for silicon at room temperature} \]
\[ \varepsilon_{si} = 10^{-12} \text{ F/cm} \quad \varepsilon_{ox} = 3.45 \times 10^{-13} \text{ F/cm} \]
1. (30 points)
A CMOS inverter has the following voltage transfer characteristics and transistor data.

\[ V_{IN} = 1.2V \]

\[ V_{IN} = 1.5V \]

\[ V_{IN} = 1.8V \]

\[ V_{OUT}(VOLTS) \]

\[ W_p/1.5\mu \]

\[ V_{IN} = 1.2V \]

\[ V_{IN} = 1.5V \]

\[ V_{IN} = 1.8V \]

\[ 3V \]

\[ 6\mu/1.5\mu \]

NMOS Data
\[ \mu_pC_{ox} = 50 \mu A/V^2 \]
\[ V_{Tn} = 0.5V \]

PMOS Data
\[ \mu_pC_{ox} = 25 \mu A/V^2 \]
\[ V_{Tp} = -0.5V \]

a) Calculate \( W_p \) such that \( -I_{DP} = I_{DN} = 100\mu A \) at \( V_{IN} = V_M \).
b) Calculate the NMOS transconductance, $g_{mn}$, at $V_{IN} = V_M$.

c) Calculate ($\lambda_n + \lambda_p$).
An inverter with a p-channel current source has the same current 100µA flowing through the p and n channel device at $V_{IN}=V_M$ is shown below. This inverter has different p-channel sizing but the same transistor data.

NMOS Data
$\mu_n C_{ox} = 50 \, \mu A/V^2$
$V_{Tn} = 0.5V$

PMOS Data
$\mu_p C_{ox} = 25 \, \mu A/V^2$
$V_{Tp} = -0.5V$

d) What is the value of the $V_B$ such that $-I_{Dp} = I_{Dn} = 100\mu A$ at $V_{IN} = V_M$?
e) Calculate the voltage gain at $V_{IN} = V_M$. 
2. (35 points)
You are given a \textit{pn} junction diode where you have microscopy and chemical staining techniques to determine the area of the diode is 10^4 \text{cm}^2 and the n-type region is degenerately doped (\textgreater \textgreater 10^{19} \text{cm}^{-3}).

You have access to a capacitance-voltage measurement system and have measured three data points and have been asked to determine some of the diode parameters.

<table>
<thead>
<tr>
<th>V</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.0V</td>
<td>0.68pF</td>
</tr>
<tr>
<td>0V</td>
<td>1pF</td>
</tr>
<tr>
<td>0.6V</td>
<td>3.2nF</td>
</tr>
</tbody>
</table>

Note: If you could not calculate some of the parameters, leave your answer in terms of those unknown parameters.

a) Calculate the depletion region width at thermal equilibrium, \( x_{po} \).
b) Calculate the built-in potential $\Phi_B$ for this diode.

c) Calculate the doping concentration of the p-type region of the diode.
d) Calculate the physical width of the p-type region. Ignore the depletion region.
3. (35 Points)

A silicon npn bipolar transistor with Ebers-Moll parameters $I_n(Si) = 10^{-15}$ A, and $\beta_f(Si)=100$ is biased as shown below.

![Bipolar Transistor Diagram]

$\begin{align*}
I_B & = 100 \mu A \\
V_{CE} & = 2 V
\end{align*}$

a) What is the region of operation? Explain your answer.
b) Calculate the collector current $I_c$.

c) Calculate the base-emitter voltage, $V_{BE}$. 
d) A second *npn* bipolar transistor is fabricated with the emitter and collector regions consisting of Si, while the base region consists of another semiconductor, called SiGe, which has an intrinsic carrier concentration \( n_{\text{SiGe}} = 1 \times 10^{11} \text{ cm}^{-3} \). Assume that the diffusivities \( D_n \) and \( D_p \) in SiGe are identical to those for Si, and that the width of the emitter, base, and collector regions are the same in both devices, i.e. \( W_E(\text{Si}) = W_E(\text{SiGe}) \), \( W_B(\text{Si}) = W_B(\text{SiGe}) \), and \( W_C(\text{Si}) = W_C(\text{SiGe}) \). For both devices, \( N_{\text{dE}} = 10^{19} \text{ cm}^{-3} \), \( N_{\text{ab}} = 10^{17} \text{ cm}^{-3} \), and \( N_{\text{dc}} = 10^{16} \text{ cm}^{-3} \). Assume that recombination only takes place at the contacts. For \( V_{\text{BE}} = 0.6 \text{V} \) and \( V_{\text{BC}} = -1.4 \text{V} \), sketch the minority carrier densities in the emitter, base, and collector, for both the Si and SiGe transistors, on the axes below (note that the space-charge regions are omitted and only the quasi-neutral regions are shown). Label the sketches with the numerical values at the contacts and at the edges of the space-charge regions. (i.e. neglect the space-charge regions)
e) For the Si and SiGe bipolar transistors and bias conditions given in (d), calculate the ratio of the collector saturation currents, $I_{S}(\text{SiGe})/I_{S}(\text{Si})$.

f) For the Si and SiGe bipolar transistors and bias conditions in (d), calculate the ratio of the forward active current gains, $\beta_{F}(\text{SiGe})/\beta_{F}(\text{Si})$. 
g) The Si and SiGe bipolar transistors in (d) are now biased in the forward active region with the same $V_{BC}$, and $V_{BE}$ adjusted such that the collector currents of the two devices are equal, i.e. $I_c(Si)=I_c(SiGe)$. Under these bias conditions, calculate the ratio of the input resistances of the two devices, $r_\pi(SiGe)/r_\pi(Si)$. 