NAME: __________________________________________

GEORGIA INSTITUTE OF TECHNOLOGY
School of Electrical and Computer Engineering

ECE 3040-E    Exam 2    Closed Book and Notes
Spring 2003    February 27, 2003

General Instructions:

1. Write on one side of the paper. (1 Pt.)

2. Put answers to all questions in the spaces provided on the test. (1 Pt.)

3. Show all work for full credit on questions requiring calculations. No credit will be given for answers alone, without supporting work.

4. Problems and questions are weighted as indicated. The maximum score is 100 points.

5. If you need more paper (provided in class), remove the staple from the exam and, when finished, arrange the test in order. Place the extra pages with supporting work in the test behind the page where the problem appears and indicate accordingly. Staple the entire test together so that there are no loose pages. (1 Pt.)

TEST SCORE: ____________________________ / 100

I certify that I have neither given nor received any assistance while taking this test from anyone.

_________________________________________ (Signature) (1 Pt.)

☐ Place a check mark in the box if you observed any suspicious actions while taking this test.
**Formula Sheet:**  Equations/Constants that you may, or may not, need are listed below:

<table>
<thead>
<tr>
<th>Parameters for Silicon</th>
<th>n-type material</th>
<th>p-type material</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>300</td>
<td>300</td>
<td>°K</td>
</tr>
<tr>
<td>$n_i$ (intrinsic carrier concentration)</td>
<td>$1.18 \times 10^{10}$</td>
<td>$1.18 \times 10^{10}$</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$T$ (minority carrier lifetime)</td>
<td>1</td>
<td>2</td>
<td>µs</td>
</tr>
<tr>
<td>$D$ (diffusion Coefficient)</td>
<td>32.5</td>
<td>11.4</td>
<td>cm$^2$/sec</td>
</tr>
<tr>
<td>$\mu$ (carrier mobility)</td>
<td>1248</td>
<td>437</td>
<td>cm$^2$/V·sec</td>
</tr>
<tr>
<td>$E_G$ (band gap energy)</td>
<td>1.12</td>
<td>1.12</td>
<td>eV</td>
</tr>
</tbody>
</table>
## PHYSICAL CONSTANTS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$</td>
<td>Electronic charge (magnitude)</td>
<td>$1.60 \times 10^{-19}$ coul</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Permittivity of free space</td>
<td>$8.85 \times 10^{-14}$ farad/cm</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann constant</td>
<td>$8.617 \times 10^{-5}$ eV/K</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck constant</td>
<td>$6.63 \times 10^{-34}$ joule-sec</td>
</tr>
<tr>
<td>$m_0$</td>
<td>Electron rest mass</td>
<td>$9.11 \times 10^{-31}$ kg</td>
</tr>
<tr>
<td>$kT$</td>
<td>Thermal energy</td>
<td>$0.0259$ eV ($T = 300$ K)</td>
</tr>
<tr>
<td>$kT/q$</td>
<td>Thermal voltage</td>
<td>$0.0259$ V ($T = 300$ K)</td>
</tr>
</tbody>
</table>

## CONVERSION FACTORS

- $1 \text{Å} = 10^{-8}$ cm $= 10^{-10}$ m
- $1 \mu$m $= 10^{-4}$ cm $= 10^{-6}$ m
- $1$ eV $= 1.60 \times 10^{-19}$ joules
**Table 2.4** Carrier Modeling Equation Summary.

### Density of States and Fermi Function

\[
g_c(E) = \frac{m^*_n \sqrt{2m^*_n (E - E_c)}}{\pi^2 \hbar^3}, \quad E \geq E_c
\]

\[
g_v(E) = \frac{m^*_p \sqrt{2m^*_p (E_v - E)}}{\pi^2 \hbar^3}, \quad E \leq E_v
\]

\[
f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}
\]

### Carrier Concentration Relationships

\[
n = N_C \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_c) \quad N_C = 2 \left[ \frac{m^*_n kT}{2\pi \hbar^2} \right]^{3/2}
\]

\[
p = N_v \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_v) \quad N_v = 2 \left[ \frac{m^*_p kT}{2\pi \hbar^2} \right]^{3/2}
\]

\[
n = N_C e^{(E_v - E_c)/kT}
\]

\[
p = N_v e^{(E_v - E_F)/kT}
\]

### \(n_i\), np-Product, and Charge Neutrality

\[
n_i = \sqrt{N_C N_v} e^{-E_d/2kT}
\]

\[
p = n_i^2
\]

\[
p - n + N_D - N_A = 0
\]

### \(n\), \(p\), and Fermi Level Computational Relationships

\[
n = \frac{N_D - N_A}{2} + \left[ \left( \frac{N_D - N_A}{2} \right)^2 + n_i^2 \right]^{1/2}
\]

\[
E_i = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln \left( \frac{m^*_p}{m^*_n} \right)
\]

\[
n \approx N_D \quad N_D \gg N_A, N_D \gg n_i
\]

\[
p \approx n_i^2 / N_D
\]

\[
p \approx N_A \quad N_A \gg N_D, N_A \gg n_i
\]

\[
n \approx n_i^2 / N_A
\]

\[
E_F - E_i = kT \ln(n_i/n_i) = -kT \ln(p/n_i)
\]

\[
E_F - E_i = kT \ln(N_D/n_i) \quad N_D \gg N_A, N_D \gg n_i
\]

\[
E_i - E_F = kT \ln(N_A/n_i) \quad N_A \gg N_D, N_A \gg n_i
\]
Table 3.3 Carrier Action Equation Summary.

**Equations of State**
\[
\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot \mathbf{J}_n + \frac{\partial n}{\partial t} \bigg|_{\text{thermal R–G}} + \frac{\partial n}{\partial t} \bigg|_{\text{other processes}}
\]
\[
\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot \mathbf{J}_p + \frac{\partial p}{\partial t} \bigg|_{\text{thermal R–G}} + \frac{\partial p}{\partial t} \bigg|_{\text{other processes}}
\]
\[
\frac{\partial \Delta n_p}{\partial t} = D_n \frac{\partial^2 \Delta n_p}{\partial x^2} - \frac{\Delta n_p}{\tau_n} + G_L
\]
\[
\frac{\partial \Delta p_n}{\partial t} = D_p \frac{\partial^2 \Delta p_n}{\partial x^2} - \frac{\Delta p_n}{\tau_p} + G_L
\]

**Current and R–G Relationships**
\[
\mathbf{J}_n = \mathbf{J}_{n,\text{drift}} + \mathbf{J}_{n,\text{diff}} = q \mu_n n \mathbf{E} + q D_n \nabla n
\]
\[
\mathbf{J}_p = \mathbf{J}_{p,\text{drift}} + \mathbf{J}_{p,\text{diff}} = q \mu_p p \mathbf{E} - q D_p \nabla p
\]
\[
\mathbf{J} = \mathbf{J}_n + \mathbf{J}_p
\]

**Key Parametric Relationships**
\[
L_n = \sqrt{D_n \tau_n}
\]
\[
L_p = \sqrt{D_p \tau_p}
\]
\[
\frac{D_n}{\mu_n} = \frac{kT}{q}
\]
\[
\frac{D_p}{\mu_p} = \frac{kT}{q}
\]
\[
\frac{\tau_n}{c_n N_T} = \frac{1}{c_n N_T}
\]
\[
\frac{\tau_p}{c_p N_T} = \frac{1}{c_p N_T}
\]

**Resistivity and Electrostatic Relationships**
\[
\rho = \frac{1}{q(\mu_n n + \mu_p p)}
\]
\[
\rho = \frac{1}{q \mu_n N_D} \quad \ldots \text{n-type semiconductor}
\]
\[
\rho = \frac{1}{q \mu_p N_A} \quad \ldots \text{p-type semiconductor}
\]
\[
\mathcal{E} = \frac{1}{q} \frac{dE_i}{dx} = \frac{1}{q} \frac{dE_i}{dx} = \frac{1}{q} \frac{dE_i}{dx}
\]
\[
V = -\frac{1}{q} (E_c - E_{\text{ref}})
\]

**Quasi-Fermi Level Relationships**
\[
F_N = E_i + kT \ln \left( \frac{n}{n_i} \right)
\]
\[
\mathbf{J}_n = \mu_n n \nabla F_N
\]
\[
F_p = E_i - kT \ln \left( \frac{p}{n_i} \right)
\]
\[
\mathbf{J}_p = \mu_p p \nabla F_P
\]
Part A – Continuity Concepts (16 Points)

1. An infinitely long piece of silicon semiconductor doped with a donor concentration of $10^{16}$ cm$^{-3}$ is uniformly illuminated with light at a particular point in time (time = $t = 0$), as illustrated in the figure below (assume low level injection). Symbolically label all important (applicable) parameters (e.g., $N_D$, $N_A$, $n_o$, $p_o$, $n_i$, $\tau_n$, $\tau_p$, $\Delta n_p$, $\Delta p_n$, $L_n$, $L_p$, etc.) –equations are not necessary to support your answer–.

(a) Qualitatively sketch the electron concentration $n(t)$ and the hole concentration $p(t)$ as a function of time at the point of incidence ($x = 0$) in the graph below. (8 pts)
(b) For the same situation, qualitatively sketch the electron concentration \( n(x) \) and the hole concentration \( p(x) \) as a function of distance \( (x) \) into the semiconductor for steady-state conditions (time \( \rightarrow \infty \)).

\( \text{(8 pts)} \)
Part B – The Diode (35 Points)

1. Why is the “space-charge” region of a diode also called the “depletion” region? (3 pts)

2. Qualitatively, _________________ describes the average time a carrier takes to cross the depletion region. (2 pts)

3. **True or False**: In creating a sharp step junction profile, the diffusion fabrication process is more effective than ion implantation. (2 pts)
4. Qualitatively draw the electrostatic graphs (band diagram, voltage, electric field, and charge) of a p+n (N_A >> N_D) junction diode at equilibrium conditions. Carefully label the depletion widths and the relative distances into the semiconductor from the metallurgical junction to the quasi-neutral regions. Symbolically label all important (applicable) parameters (e.g., x_n, x_p, N_D, N_A, V_{bi}, w, etc.). (16 pts)
5. Carefully draw the band diagram and carrier activity for a p+n junction diode when the diode is in Avalanche breakdown (label all pertinent Fermi levels and how the voltage across the diode ($v_D$) relates to the band diagram).

6. **True or False**: The effective potential barrier of a pn junction is increased when an applied forward-biasing voltage is increased.
Part C – Diode Circuits (45 Points)

1. __________________, _________________________, and __________________ are the three regions of operation of a diode. (6 pts)

2. __________________, _________________________, and __________________ are three diode models used to describe the operation of a diode (pn-junction device). In the space below, draw and label the I-V curves for the three models, including breakdown. Label $V_{on}$ and $V_{BD}$ for all three. (11 pts)

3. For the circuit shown below, draw the general qualitative transfer curve ($V_{Pin}$ as a function of $V_{in}$) in the space provided. Assume the on-voltage of the diode is 0.7 V and the breakdown voltage is 7 V. (10 pts)
4. In the space provided (to the right of the Spice code), draw the schematic being described by the Spice code below. **Label all nodes and electrical components.** (6 pts)

* Circuit
  
  Vs  vdd  0  DC  15
  Rs  vdd  vo  5k
  Do  0  vo  Dsample
  Ro  vo  0  15k
  Co  vo  0  1µ

  .model Dsample D (is=1e-17, rs=20, cjo=1p, tt=50n)

5. Draw the complete schematic of the equivalent diode circuit model (i.e., equivalent resistors, capacitors, etc.) and explain what each component represents. (12 pts)

*The “END”*