NAME: ________________________________

GEORGIA INSTITUTE OF TECHNOLOGY
School of Electrical and Computer Engineering

ECE 3040-C    Exam 1    Closed Book and Notes
Spring 2002    January 31, 2002

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

TOTAL POINTS: ________________________________ / 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.
### Parameters for Silicon

<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>$\tau$ (minority carrier lifetime)</td>
<td>1</td>
<td>2</td>
<td>ns</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
- $1\text{eV} = 1.60 \times 10^{-19}$ joules
### Table 2.4 Carrier Modeling Equation Summary

#### Density of States and Fermi Function

- \( g_n(E) = \frac{m^*_n \sqrt{2m^*_n(E - E_F)}}{\pi^2 \hbar^3} \), \( E \geq E_F \)
- \( g_p(E) = \frac{m^*_p \sqrt{2m^*_p(E_p - E)}}{\pi^2 \hbar^3} \), \( E \leq E_F \)
- \( f(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \)

#### Carrier Concentration Relationships

- \( n = N_C \frac{2}{\sqrt{\pi}} F_{1/2}(\gamma_n) \quad N_C = 2 \left( \frac{m^*_n kT}{2\pi\hbar^2} \right)^{1/2} \)
- \( p = N_P \frac{2}{\sqrt{\pi}} F_{1/2}(\gamma_p) \quad N_P = 2 \left( \frac{m^*_p kT}{2\pi\hbar^2} \right)^{1/2} \)

#### \( n, p \)-Product, and Charge Neutrality

- \( n_p = n_i^2 \)
- \( n - p + N_D - N_A = 0 \)

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

- \( n = \frac{N_D - N_A}{2} + \left[ \left( \frac{N_D - N_A}{2} \right)^2 + n_i^2 \right]^{1/2} \)
- \( E_F = E_i + \frac{3}{4} kT \ln \left( \frac{m^*_n}{m^*_n} \right) \)
- \( N_D \gg N_A, N_D \gg n_i \)
- \( E_F - E_i = kT \ln(n_i/n_A) = -kT \ln(p/n_i) \)

- \( p = n_i^2/N_D \)
- \( N_A \gg N_D, N_A \gg n_i \)
- \( E_F - E_i = kT \ln(n_i/N_A) \)

- \( n = n_i^2/N_A \)
- \( E_F - E_i = kT \ln(n_i/N_A) \)
- \( N_A \gg N_D, N_A \gg n_i \)

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

### Equations of State

\[
\begin{align*}
\frac{\partial n}{\partial t} &= \frac{1}{q} \nabla \cdot \mathbf{J}_n + \frac{\partial \mu_n}{\partial n} \left( \text{drift} \right) + \frac{\partial \mu_n}{\partial n} \left( \text{diffusion} \right) + \frac{\partial n}{\partial t} \left( \text{carrier processes} \right) \\
\frac{\partial p}{\partial t} &= -\frac{1}{q} \nabla \cdot \mathbf{J}_p + \frac{\partial \mu_p}{\partial p} \left( \text{drift} \right) + \frac{\partial \mu_p}{\partial p} \left( \text{diffusion} \right) + \frac{\partial p}{\partial t} \left( \text{carrier processes} \right) \\
\frac{\partial \Delta n}{\partial t} &= D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_n} + G_t \\
\frac{\partial \Delta p}{\partial t} &= D_p \frac{\partial^2 \Delta p}{\partial x^2} - \frac{\Delta p}{\tau_p} + G_t
\end{align*}
\]

### Current and R–G Relationships

\[
\begin{align*}
\mathbf{J}_n &= J_{\text{diff}} + J_{\text{drift}} = q\mu_n n \mathbf{E} + qD_n \nabla n \\
\mathbf{J}_p &= J_{\text{diff}} + J_{\text{drift}} = q\mu_p p \mathbf{E} - qD_p \nabla p \\
\mathbf{J} &= \mathbf{J}_n + \mathbf{J}_p
\end{align*}
\]

### Key Parametric Relationships

\[
\begin{align*}
L_n &= \sqrt{D_n \tau_n} \\
L_p &= \sqrt{D_p \tau_p}
\end{align*}
\]

### Resistivity and Electrostastic Relationships

\[
\rho = \frac{1}{q(\mu_n n + \mu_p p)} \\
\rho = \frac{1}{q\mu_n n_D} \quad \ldots \quad \text{n-type semiconductor} \\
\rho = \frac{1}{q\mu_p n_A} \quad \ldots \quad \text{p-type semiconductor}
\]

\[
\begin{align*}
\xi &= \frac{1}{q} \frac{dE_n}{dx} = \frac{1}{q} \frac{dE_p}{dx} = \frac{1}{q} \frac{dE_V}{dx} \\
V &= \frac{1}{q} (E_n - E_{\text{ref}})
\end{align*}
\]

### Quasi-Fermi Level Relationships

\[
\begin{align*}
F_n &= E_n + kT \ln \left( \frac{n}{n_i} \right) \\
J_n &= \mu_n n \mathbf{F}_n \\
F_p &= E_p - kT \ln \left( \frac{p}{p_i} \right) \\
J_p &= \mu_p p \mathbf{F}_p
\end{align*}
\]
Part A – (26 Points)

1. A “Zincblende” structure is formed by interpenetrating two ________________ unit cells. (2 pts)

2. The crystal structure for silicon and germanium is identified as ________________ . (2 pts)

3. A Miller index of ______ represents a vector that is normal to the x-y plane. (4 pts)

4. Insulators, metals, and semiconductors exhibit ________________ , ________________ , and ______ ________________ bonding, respectively. (6 pts)

5. True or false: Most silicon wafers used to make ICs have a polycrystalline structure. (2 pts)

6. How many atoms are there in a bcc lattice? ________________ (2 pts)

7. What is the radius of each atom in a body-centered cubic (bcc) lattice structure with lattice constant “a,” assuming all atoms are rigid spheres with radii equal to ½ the distance between nearest neighbors (radius = distance_{middle-to-middle-of-sphere} ÷ 2)? ________________ (8 pts)
Part B – (31 Points)

1. When the Fermi level \( E_F \) is closer to the conduction band than the valence band, the material is said to be _______ -type. (2 pts)

2. When elements in Group III of the periodic table are used as dopants, the material produced is _______________ -type. (2 pts)

3. Yes or no: Is \( E_{\text{Fermi}} = E_i \) for an intrinsic material? (2 pts)

4. The __________________ energy is characterized by the difference of energies \( E_c \) and \( E_v \) \( (E_c - E_v) \). (2 pts)

5. A silicon sample is uniformly doped with acceptor atoms at a concentration of \( 9 \times 10^{15} \text{ cm}^{-3} \) and donor atoms at a concentration of \( 10^{16} \text{ cm}^{-3} \) \( (n_i = 10^{16} \text{ cm}^{-3}, E_G = 1.015 \text{ eV}, \text{ and } m_p^* / m_n^* = 0.719 @ 650 \text{oK}) \).

a. Determine the equilibrium electron and hole concentrations inside the silicon sample at 650 \text{oK}.

\[
\begin{align*}
n &= \text{_________________________} \quad (4.5 \text{ pts}) \\
p &= \text{_________________________} \quad (4.5 \text{ pts})
\end{align*}
\]
b. Carefully draw the band diagram of the semiconductor indicating where $E_i$, $E_f$, and $E_C$ are relative to $E_V$, qualitatively only. (9 pts)

c. Where is $E_i$ relative to the mid-band gap ($E_V + E_G/2$)?

   Below / Above / at the Same Level (5 pts)
Part C – (39 Points)

1. Band bending in semiconductors is caused by __________________________. (2 pts)

2. A superimposed electric field on a semiconductor produces ____________ current while ________ ____________ current results because of a ________________ gradient in the material. (6 pts)

For questions 3 and 4, circle the most appropriate answer.

3. Carrier mobility decreases / increases / remains constant with increasing temperatures and decreases / increases / remains constant with increasing doping concentrations, as long as \( N_A \) or \( N_D \) are less than \( n_i \). (4 pts)

4. Resistivity decreases / increases / remains constant with an increase in mobility. (2 pts)

5. True or false: A constant \( E_F \), with respect to distance into the semiconductor, implies non-equilibrium conditions exist. (2 pts)

6. True or false: The rate of excess hole (\( h^+ \)) decay in n-type semiconductors is directly proportional to the intrinsic electron concentration, as far as indirect recombination is concerned. (2 pts)

7. True or false: A significant change is seen in electron-carrier concentration, under low-level injection conditions, when excess carriers are generated in an n-type semiconductor. (2 pts)
8. A cylindrical silicon rod is 10 cm long and has a cross sectional area of 2 cm$^2$. The rod is uniformly doped with $N_A = 10^{16}$ cm$^{-3}$ and has a voltage of 5 V applied across its ends –assume the rod is at room temperature–.

a. Find the total current flowing through the rod. $I =$ ________________ (10 pts)

b. Find the current due to electrons. $I_n =$ ________________ (9 pts)