NAME: ____________________________________________

GEORGIA INSTITUTE OF TECHNOLOGY
School of Electrical and Computer Engineering

ECE 3040-E    Exam 1    Closed Book and Notes
Spring 2003    January 30, 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>Ms</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>$\hbar$</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 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

\[
g_C(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_C)}}{\pi^2 \hbar^3}, \quad E \geq E_C
\]

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

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

#### Carrier Concentration Relationships

\[
n = N_C \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_n)
\]

\[
n_C = 2 \left[ \frac{m_n^* kT}{2 \pi \hbar^2} \right]^{3/2}
\]

\[
p = N_V \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_v)
\]

\[
n_V = 2 \left[ \frac{m_p^* kT}{2 \pi \hbar^2} \right]^{3/2}
\]

\[
n = N_C e^{(E_k - E_C)/kT}
\]

\[
p = N_V e^{(E_V - E_C)/kT}
\]

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

\[
n_p = n_i^2
\]

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

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

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

\[
E_F = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln \left( \frac{m_n^*}{m_p^*} \right)
\]

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

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

\[
p = n_i^2 / N_D
\]

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

\[
N_A \gg N_D, N_A \gg n_i
\]

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

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

\[
N_A \gg N_D, N_A \gg n_i
\]
### Equations of State

\[
\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot J_N + \frac{\partial n}{\partial t}_{\text{thermal \ R-G}} + \frac{\partial n}{\partial t}_{\text{other processes}} \\
\frac{\partial p}{\partial t} = \frac{1}{q} \nabla \cdot J_p + \frac{\partial p}{\partial t}_{\text{thermal \ R-G}} + \frac{\partial p}{\partial t}_{\text{other processes}} \\
\frac{\partial^2 n}{\partial x^2} = \frac{D_n}{\tau_n} \frac{\partial^2 n}{\partial x^2} - \frac{\Delta n_p}{\tau_p} + G_L \\
\frac{\partial^2 p}{\partial x^2} = \frac{D_p}{\tau_p} \frac{\partial^2 p}{\partial x^2} - \frac{\Delta p_n}{\tau_n} + G_L
\]

### Current and R–G Relationships

\[
J_N = J_{N,\text{drift}} + J_{N,\text{diff}} = q\mu_n n \xi + qD_n \nabla n \\
J_p = J_{p,\text{drift}} + J_{p,\text{diff}} = q\mu_p p \xi - qD_p \nabla p
\]

\[
J = J_N + J_p
\]

### Key Parametric Relationships

\[
L_N = \sqrt{D_n \tau_n} \\
L_p = \sqrt{D_p \tau_p}
\]

\[
\frac{D_n}{\mu_n} = \frac{kT}{q} \\
\frac{D_p}{\mu_p} = \frac{kT}{q}
\]

\[
\tau_n = \frac{1}{c_n N_T} \\
\tau_p = \frac{1}{c_p N_T}
\]

### Resistivity and Electrostatic Relationships

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

\[
\xi = \frac{1}{q} \frac{dE_i}{dx} = \frac{1}{q} \frac{dE_i}{dx} = \frac{1}{q} \frac{dE_i}{dx} \\
V = -\frac{1}{q}(E_i - E_{\text{ref}})
\]

### Quasi-Fermi Level Relationships

\[
F_N = E_i + kT \ln \left( \frac{n_i}{n} \right) \\
J_N = \mu_n n \nabla F_N
\]

\[
F_p = E_i - kT \ln \left( \frac{p_i}{p} \right) \\
J_p = \mu_p p \nabla F_p
\]
Part A – (28 Points)

1. In a ________________ bond, each atom has four (4) nearest neighbors. (2 pts)

2. A ________________ structure is created by interpenetrating two Face-Centered Cubic unit cells. (2 pts)

3. The crystal lattice for Gallium Arsenide (GaAs) is identified as Simple Cubic / BCC / FCC / Diamond / Zincblende lattice. (2 pts)

4. In the space provided, sketch the (2 1 3) plane and the [1 3 3] vector. (6 pts)

5. ________________ / ________________ / ________________ are the three different types of crystal structures, which describe the degree of atomic order. (6 pts)

6. How many atoms are there in an fcc lattice? ________________ (2 pts)

7. What is the radius of each atom in a face-centered cubic (fcc) 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 – (32 Points)

1. When the Fermi level (E_F) is half-way between the conduction and valence band, the material is said to be __________________________ material. 

2. ______________________________________ is the energy level where there is a 50 % probability of finding an electron.

3. When elements in Groups III and IV of the periodic table are used as dopants in equal amounts, the semiconductor produced is said to be __________________________.

4. True / False: Two electrons in the same space cannot exist at the same energy level.

5. True / False: Insulators are characterized for their low resistivities.

6. The __________________________ is the energy required to break a bond and consequently promote a valence electron into the conduction band. This energy is largest / smallest / equal for materials with low conductivity.

7. In an n-type extrinsic semiconductor, promoting electrons to the conduction band implies hole carriers are also created, but in greater / smaller / equal amounts.

8. For a Gallium Arsenide (GaAs) semiconductor with an acceptor concentration of $5 \times 10^{17}$ cm$^{-3}$, find the hole concentration and the Fermi Energy level –relative to intrinsic energy level $E_i$– at room temperature (at room temperature, $n_i = 10^6$ cm$^{-3}$).
9. A silicon sample is uniformly doped with donor atoms at a concentration of $10^{16}$ cm$^{-3}$ and acceptor atoms at a concentration of $10^{13}$ cm$^{-3}$ ($n_i = 10^{10}$ cm$^{-3}$ and $E_G = 1.015$ eV). Carefully draw the band diagram of the semiconductor indicating where $E_i$, $E_F$, and $E_C$ are relative to $E_V$ and midband $E_m$ ($E_m = \left[ E_V + E_C \right] / 2$), no values are required. [Hint: $E_i \neq E_m$]
Part C – (36 Points)

1. ___________ / ___________ / ___________ are the three different charge-carrying mechanisms in semiconductors (types of current flow). (6 pts)

2. **True or False.** Mobility increases if there is an increase in scattering. (2 pts)

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 much greater than* $n_i$. (4 pts)

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

5. Resistance **decreases / increases / remains constant** with increasing semiconductor length, **decreases / increases / remains constant** with increasing semiconductor width, and **decreases / increases / remains constant** with increasing semiconductor thickness. (6 pts)

6. In the space provided, draw the band diagram for the semiconductor shown (its voltage profile is illustrated) -no values are necessary but $E_F$, $E_i$, $E_C$, and $E_V$ must all be identified and drawn-. (8 pts)

7. **True or False.** By means of impact ionization, charge carrier concentration increases. (2 pts)

8. Heat or light is **emitted / absorbed / unchanged** when a hole is created. (2 pts)

9. In photogeneration, the excess hole carrier concentration is **greater than / less than / equal to** the excess electron carrier concentration in the material. (2 pts)
10. Read this and you will get two points automatically. (2 pts)