1. Use the values of physical constants provided below.
2. SHOW YOUR WORK, and write legibly!
3. Underline box numerical answers, and specify units where appropriate.

<table>
<thead>
<tr>
<th>Physical Constants</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic charge</td>
<td>$q = 1.6\times10^{-19}$ C</td>
</tr>
<tr>
<td>Thermal voltage at 300K</td>
<td>$kT/q = 0.026$ V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties of silicon (Si) at 300K</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy band gap</td>
<td>$E_g = 1.12$ eV</td>
</tr>
<tr>
<td>Intrinsic carrier concentration</td>
<td>$n_i = 10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Permittivity</td>
<td>$\varepsilon_r = 1.0 \times 10^{12}$ F/cm</td>
</tr>
</tbody>
</table>

Problem 1 [11 points]
The equilibrium energy band diagram for a rectifying metal-Si contact is shown below. $T = 300$K. $kT \ln(10) = 0.06$ eV

\[
\Phi_B = qV_{bi} + (E_C - E_F) = 0.50 \text{ eV} + 0.2 \text{ eV} = 0.7 \text{ eV}
\]

\[
W = \sqrt{\frac{2 \varepsilon_r V_{bi}}{q N_D}} = \sqrt{\frac{2 \times 10^{-12} \times 0.5}{1.6 \times 10^{-19} \times 10^{16}}} = \sqrt{\frac{10^{-12}}{1.6 \times 10^{-3}}} = 2.5 \times 10^{-5} \text{ cm} = 0.25 \mu\text{m}
\]

d) Carefully sketch $E_c$, corresponding to a reverse bias of 0.25 V on the band diagram above. [2 pts]
e) Explain how this contact can be made to be practically ohmic. [2 pts]

Increase the dopant concentration to decrease $W$ (to $\leq 10$ mm) so that electrons can easily tunnel through the potential barrier.
Problem 2 [8 points]
Consider the following charge density distribution for a Schottky diode under reverse bias:

\[ \rho \text{ (C/cm}^3 \text{)} \quad \text{and} \quad E \text{ (V/cm)} \]

1.6x10^{-3} \quad 1.0 \quad x (\mu m) \quad 0 \quad 10^{-4} \text{ cm}

\[ \text{1 slope = } \frac{P}{E_x} = \frac{1.6 \times 10^{-3}}{10^{-12}} = 1.6 \times 10^9 \text{ V/cm}^2 \]

a) Sketch the electric field distribution on the axes provided. Indicate the numerical value of \( E \) at \( x = 0 \). [5 pts]

\[ |E(0)| = (1.6 \times 10^9 \text{ V/cm}^2) \cdot (10^{-4} \text{ cm}) = 1.6 \times 10^5 \text{ V/cm} \]

b) If the cross-sectional area of this diode is 1 mm x 1 mm, what is its small-signal capacitance? [3 pts]

\[ C = \frac{A \varepsilon_s}{\kappa} = (10^{-2}) \cdot (10^{-12}) = 10^{-14} \text{ F} = 100 \text{ pF} \]

Problem 3 [6 points]
The equilibrium energy band diagram for a uniformly doped Si sample with minority-carrier lifetime \( \tau_n = 10^{-5} \text{s} \) is shown below. Suppose this sample is illuminated uniformly with light beginning at time \( t = 0 \), generating electron-hole pairs at a rate \( G_L = 10^{19} \text{cm}^{-3} \text{s}^{-1} \) throughout the sample, so that the excess carrier concentration increases with time as shown below.

\[ \Delta n(t) = \Delta p(t) \]

\[ \tau_n G_L = (10^{-6}) \cdot (10^{19} \text{cm}^{-3} \text{s}^{-1}) \]

\[ t (s) = 10^{13} \text{cm}^{-3} \]

a) Indicate the final positions of the electron and hole quasi-Fermi levels (\( F_N \) and \( F_P \), respectively) in this sample (i.e. at \( t = \infty \)). [4 pts]

In steady state, \( \frac{\partial \Delta n}{\partial t} = -\frac{\Delta n}{\tau_n} + G_L = 0 \) \( \Rightarrow \Delta n = \tau_n G_L = 10^{13} \text{ cm}^{-3} \)

Equilibrium carrier concentrations \( \rho_0 = 10^{16} \text{cm}^{-3} \), \( n_0 = \frac{\rho_0}{\mu_e} = 10^4 \text{cm}^{-3} \)

\[ p = p_0 + \Delta p = 10^{16} + 10^{13} = 10^{16} \text{cm}^{-3} \Rightarrow F_P \text{ same as } E_F \]

\[ n = n_0 + \Delta n = 10^4 + 10^{13} = 10^{13} \text{ cm}^{-3} \Rightarrow F_N = E_i + kT \ln \left( \frac{n}{n_0} \right) \]

b) Indicate on the plot above how \( \Delta p_e(t) \) would change if \( E_F \) were to be increased. [2 pts]

- Final value would be higher
- Time to reach final value would be the same.

\[ E_i + 3kT \ln(10) \]

\[ E_i + 0.18 \text{ eV} \]