For k_B T at 300K, use 26 meV.

1. Assuming a dispersion relation

\[ E = E_C + \frac{\hbar^2}{ma^2} \left[ 1 - \cos(ka) \right] \]

where \( a = 0.3 \text{ nm} \) and \( m \) is the bare electron mass.

(a) Calculate the velocity of the electron at \( k = \pi/2a \) (a number in cm/s).

(b) Calculate the effective mass at \( k = \pi/4a \) in terms of \( m \).

(c) At \( t = 0 \), an electron is at \( x = 0 \) and \( k = 0 \) in an electric field of \( E = 10^4 \text{V/cm} \). What is the value of \( k \) (1/cm) at \( t = 1 \text{ ps} \)?

(d) What is the period of the electron oscillation assuming no scattering?
2. Calculate the quantity $E_c - E_f$ for intrinsic Si at $T=300K$ where $E_c$ is the conduction band edge and $E_f$ is the Fermi level.

3. Calculate the electron and hole densities for Si doped with both B and P such that $N_D = 10^{17}/cm^3$ and $N_A = 5\times10^{16}/cm^3$ assuming complete ionization.

4. Derive the Einstein relation for degenerate statistics relating $D_n$ to $\mu_n$. 
5. A Si bar has the following properties: \(N_A = 10^{15}/cm^3\), \(\mu_n = 1350 \text{ cm}^2/\text{Vs}\), \(\mu_p = 500 \text{ cm}^2/\text{Vs}\), \(\tau_n = \tau_p = 10^{-6}\text{s}\). The left end of the bar is illuminated so as to create \(10^{10}/cm^3\) excess electron hole pairs at \(x=0\). Assuming none of the light penetrates into the interior of the bar \((x>0)\),
(a) Determine the excess minority carrier profile.

(b) Is there current flowing? Explain.

6. For a short base (100) Si n\textsuperscript{+} p diode: \(N_D = 2e18/cm^3\), \(N_A = 2e16/cm^3\), \(W_B = 0.1 \mu\text{m}\) where \(W_B\) is the length of the neutral region of the p-side, \(\mu_n\) (on p-side) = 1200 \text{ cm}^2/\text{Vs}, \(V_A = 0.75 \text{ V}\);
(a) Calculate the diffusion current from the minority carrier diffusion equations.
(b) For $\tau_n = 0$, the electrons are in equilibrium with the holes on the p-side which means that, on the p-side, $F_n = F_p$. For these conditions, use thermionic emission theory to determine the maximum current that can flow.
7. The reverse bias leakage current, $I_{CB0}$, of an npn BJT is measured with the emitter open.
(a) Use the Ebers-Moll equations to determine $V_{BE}$. $\beta_F = 100$, $T=300K$, and $V_{BC} = -10V$. You will need to use the relation $\alpha_F I_F = \alpha_R I_R$. 
(b) On the figure at right, sketch the minority carrier electron distribution in the base.

(c) For a base doping of $1 \times 10^{18} / \text{cm}^3$, what is the minority electron distribution $n_B$, at $x = 0$ and $x = W_B$?

8. For an npn BJT at $T = 300K$ with a base width of 0.05 $\mu$m and a minority electron mobility in the base of 800 $\text{cm}^2/\text{Vs}$, what is the maximum value for the transition frequency, $f_T$?

9. For an NMOS FET with $\mu_n$ in the channel equal to 800 $\text{cm}^2/\text{Vs}$, a gate length of 0.18 $\mu$m, and $(V_{GS} - V_t) = 1 \text{V}$ what is the maximum value for the transition frequency, $f_T$, assuming the “square law” relation for $I_D$. 
10. Consider an NMOS FET with a polysilicon (poly) gate (instead of metal). The poly is heavily doped poly-crystalline Si. For p-type poly, assume that in the poly, $E_f = E_v$, and for n-type poly, assume that $E_f = E_c$. For the electrostatic calculations, you can treat the poly as a metal, i.e. there is no voltage drop in the poly. The thickness of the SiO$_2$ is 10 nm and it is grown on a 10 Ω cm p-type Si wafer. At the Si / SiO$_2$ interface there is a surface state charge of $10^{11}$ charges / cm$^2$.

(a) Calculate the threshold voltage for an n-type poly gate.

(b) Calculate the threshold voltage for a p-type poly gate.
11. For an NMOS FET we write that the electron charge per unit area under the gate is \( Q_n(y) = \text{Cox}[V_{GS} - V(y) - V_t] \). Using the same approach that we used to derive the “square law” for \( I_D \), derive an expression for the potential \( V(y) \) and the electric field component \( E_y(y) \) in saturation.