EEE112
Integrated Electronics & Design: Exercise Problem

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Contents

Exercise problems

Semiconductor Fundamentals

Atomic Density

1. What is the volume density of atoms for a face-centered cubic structure with lattice constant a_0=5 Å?

2. The lattice constant of a body-centered cubic structure is a_0 = 4.75 Å. What is the volume density of atoms?

Crystal Lattice Plane

1. What are the Miller Indices of the plane shown in figure 1?

2. A plane is described as a (123) plane. What are the intercepts on a Cartesian axes?

3. Describe the direction in Figure 2 and the plane perpendicular to it

4. Describe the lattice direction shown in Figure 3 and the corresponding perpendicular plane

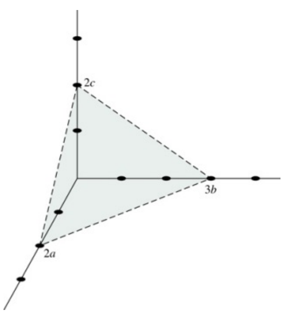


Figure 1

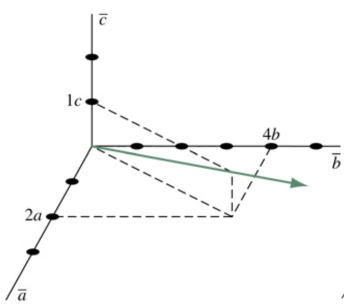


Figure 2

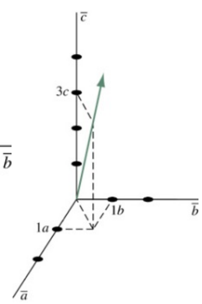


Figure 3

Energy Levels

1. Determine the first 3 allowed electron energies in the hydrogen atom

$$E_n = - m_0e^4/(4\pi\varepsilon_0)^2 2((h/2\pi)^2)n^2 \text{ where}$$

m_0=mass of an electron = 9.11×10^{-31} kg
e=electron charge=1.6×10^{-19} C
h=Planck Constant=6.625×10^{-34} J-s
ε_0=Permittivity of free space=8.85×10^{-12} F/m
n is the energy level

2. For a one electron atom, determine the value of n such that $E_{n+1} – E_n < 0.2$eV

Energy Band

1. Calculate the change in Kinetic Energy of an electron when the velocity increases from 10^7 cm/s by 1 cm/s

Kinetic energy = $(1/2)mv^2$

2. An electron travelling at $v_0=2x10^7$ cm/s increases in speed so that the change in Kinetic Energy is 10^{-8} eV. Determine the increase in electron speed

Density of States and Probability

1. Find the density of states for an electron per unit volume between 0 – 1 eV.

$$N = \int_{E_1}^{E_2} g(E)dE = \int_{E_1}^{E_2} \frac{4\pi(2m_p)^{3/2}}{h^3}\sqrt{E_v - E}dE$$

2. Find the density of states for an electron per unit volume between 1 eV – 2 eV.

3. Determine the probability that an electron occupies a state 3kT above E_F at T=300 K

4. If E_F=0.3 eV, determine the probability of a state being occupied by an electron at i) $E=E_c+kT$ and ii) $E=E_c+2kT$ at T=300 K

$$f_F(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$$

5. The Fermi Energy for a material is 6.25 eV and electrons follow the Fermi-Dirac distribution, Calculate the temperature for a 1% probability that a state 0.3 eV below the Fermi energy is empty.

6. The Fermi Energy for a material is 5.5 eV and electrons follow the Fermi-Dirac distribution, Calculate the temperature for a 0.5 % probability that a state 0.2 eV above the Fermi energy has an electron.

7. Calculate the energy in terms of kT and E_F at which the Boltzman approximation and the Fermi-Dirac function is 5% of the Fermi function

8. Repeat question 5 for a 1% variation

9. Calculate the probability that an energy state in the conduction band at $E=E_C + kT$ is occupied by an electron and calculate the thermal equilibrium electron concentration in silicon at T=300 K. $E_F=E_C - 0.2$ eV, for silicon at T=300 K $N_c = 2.8x10^{19}$ cm^{-3}

10. Repeat question 9 when $E_F=E_C - 0.25$ eV

11. Calculate the probability that an energy state in the valence band at $E=E_V$-kT is empty of an electron and calculate the thermal equilibrium hole concentration in silicon at T=300 K. $E_F=E_V+0.25$ eV, for silicon at T=350 K $N_v=1.04x10^{19}$ cm^{-3}

12. Calculate the thermal equilibrium hole concentration in silicon at T=300 K, when $E_F=E_v+0.2$ eV

13. Calculate the intrinsic carrier concentration in silicon at T=350 K and 400 K.N_C and N_V vary with $T^{3/2}$. Assume that $E_G=1.12$ eV

14. Calculate the intrinsic carrier concentration in GaAs at T=200 K and T=400 K

15. Determine the position of the intrinsic Fermi level with respect to the centre of the bandgap in silicon at T=300 K. $m_n^*=1.08m_0$ and $m_p^*=0.56m_0$

16. Repeat question 15 for GaAs at T=300 K

Carrier Concentration

1. Find the thermal equilibrium carrier concentrations in silicon at T=300 K, assuming that $E_F=E_V+0.25$ eV. If $E_G=1.12$ eV, then $E_F=E_C-0.87$ eV.

2. Repeat question 1 when the Fermi level is 0.2 eV below the conduction band

3. Determine the hole concentration in silicon at T=300 K if the electron concentration is $n_0=1x10^{16}$ cm^{-3}

4. Repeat question3 when $n_0=1x10^5$ cm^{-3}.

5.Determine the thermal equilibrium electron and hole concentrations in silicon doped with Phosphorus at a concentration of $N_d=2x10^{16}$ cm^{-3}, assuming $N_a=0$

6. The concentration of majority carriers in n-type silicon at T=300 K is to be $n_0=10^{15}$ cm^{-3}. Determine the concentration of phosphorous atoms to be added and the concentration of minority carriers.

7. Calculate the thermal equilibrium electron and hole concentration in a Germanium sample at T=300 K in which $N_d=5x10^{13}$ and $N_a=0$. Assume $n_i=2.4x10^{13}$ cm^{-3}

8. Germanium is doped with donors at a concentration of $N_d=10^{14}$ cm^{-3}. Calculate the thermal equilibrium concentration of electrons and holes.

9. Consider a compensated p-type doped silicon semiconductor at T=300 K with doping concentrations of $N_a=2x10^{16}$ cm^{-3} and $N_d=5x10^{15}$ cm^{-3}. Find the thermal equilibrium carrier concentrations

10. Consider a compensated germanium semiconductor at T=300 K doped at $N_a=5x10^{13}$ cm^{-3}, $N_d=1x10^{13}$ cm^{-3}. Find a thermal equilibrium electron and hole concentrations.

11. An n-type silicon device is to operate at T=450 K. At this temperature the intrinsic carrier concentration must contribute no more than 3% of the total electron concentration. Determine the minimum doping concentration required.

12. An n-type germanium device is to operate at T=400 K. At this temperature the intrinsic carrier concentration must not contribute more than 10% of the total electron concentration. Determine the minimum donor concentration required.

13. A silicon device operates at T=300 K, it contains an acceptor impurity concentration of $N_d=10^{16}$ cm^{-3}. Determine the donor concentration that must be added so that the silicon is n-type and the Fermi energy is 0.2 eV below the conduction band.

14. Determine the position of the Fermi level with respect to the valence band in p-type GaAs at T=300 K where the doping concentrations are $N_a=5x10^{16}$ cm^{-3} and $N_d=4x10^{15}$ cm^{-3}.

15. Consider p-type silicon at T=300 K doped with Boron. Assuming the limit at which the Boltzman approximation is $E_F - E_V=3kT$. Determine the Fermi level and the maximum doping at which the Boltzman approximation is true.

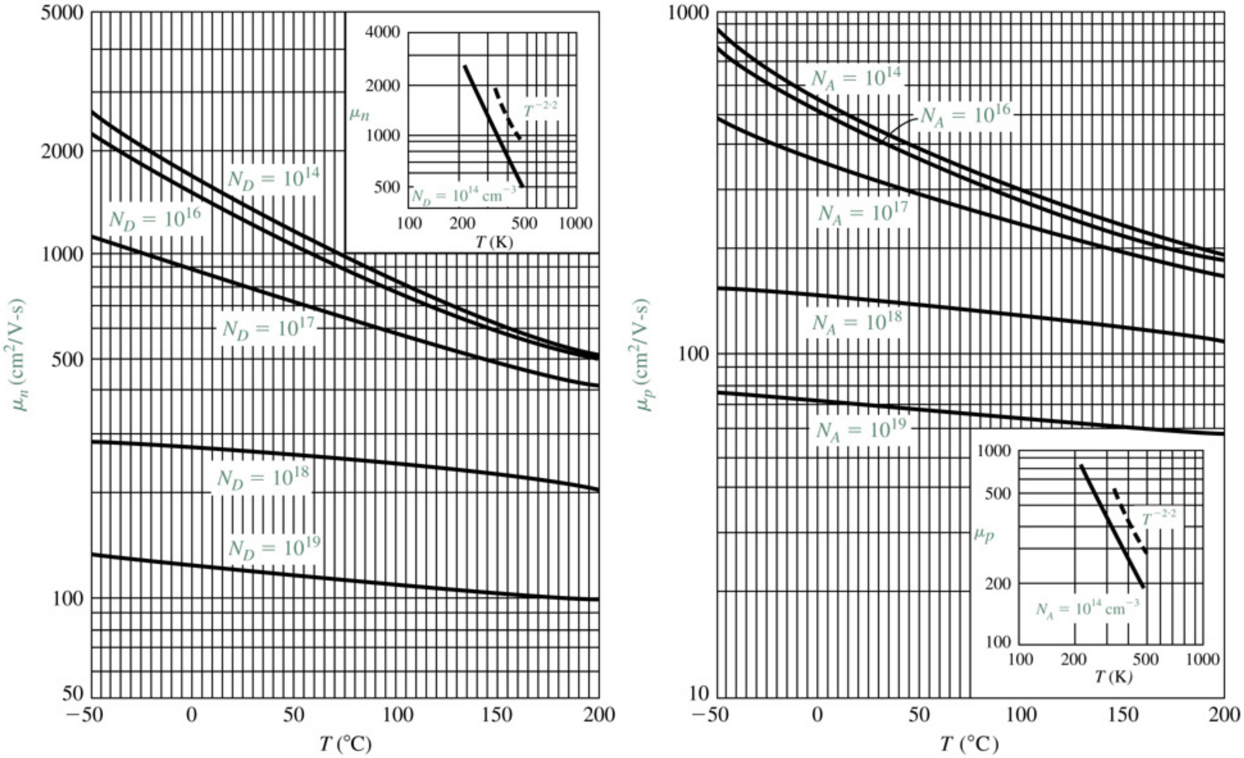
16. Consider n-type silicon at T=300 K doped with phosphorous. Determine the doping concentration such that $E_d-E_F=4.6kT$.

Drift and Diffusion of Carriers

	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)
Silicon	1350	480
Galium Arsenide	8500	400
Germanium	3900	1900

1. Consider a silicon semiconductor at T=300 K with an impurity doping concentration of $N_d=10^{16}$ cm^{-3}, $N_a=0$. The electron and hole mobilities are given in the table. Calculate the drift current densities for an applied electric field of $\mathcal{E}$=35 V/m

2. Consider a GaAs sample at T=300 K with doping concentrations $N_a=0$ and $N_d=10^{16}$ cm^{-3}. The electron hole mobilities are shown in the table. Calculate the drift current density for an applied electric field $\mathcal{E}$=10 V/m.

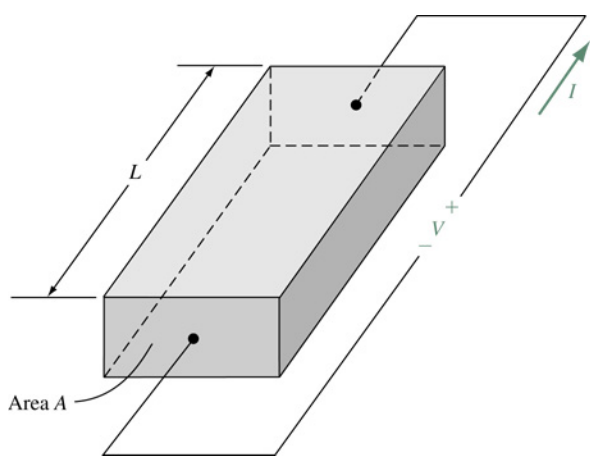


(a) (b)

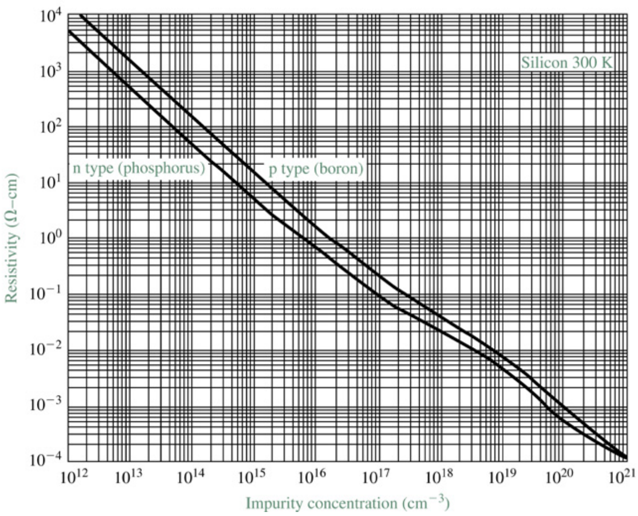
3. Find the electron mobility for i) $N_d=10^{17}$ cm^{-3}, T=150 K and for ii) $N_d=10^{16}$ cm^{-3}, T=0. Find the hole mobility for i) $N_a=10^{16}$ cm^{-3}, T=50 K and for ii) $N_d=10^{17}$ cm^{-3}, T=150 K.

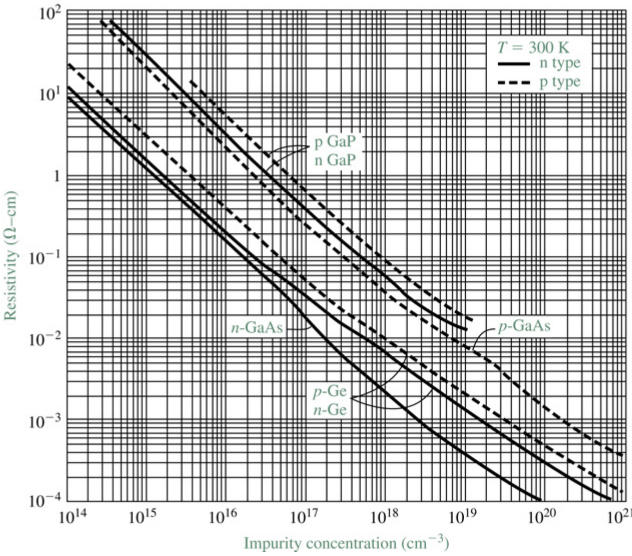
4. Use the graphs above to find the electron and hole mobilities in silicon for i) $N_d=10^{17}$ cm^{-3}, $N_a=5\text{x}10^{16}$ cm^{-3} and ii) in GaAs for $N_d=N_a=10^{17}$ cm^{-3} T=150 K

5. Consider a bar of silicon at T=300 K uniformly doped with acceptors and geometry as shown. For an applied voltage of 5 V, a current of 2 mA is required. Current density must be no larger than J_{drf}=100 A/cm^2. Find the required cross-sectional area, length and doping concentration.



6. For a semiconductor device at T=300 K, the required material is to be n-type with a resistivity ρ=0.1 Ω-cm. Determine the required impurity doping concentrations and the resulting electron mobility. Use the figures below.





7. A silicon semiconductor at T=300 K and with the geometry shown above is initially doped with donors at a concentration of $N_d=5\text{x}10^{15}$ cm^{-3}. Acceptors are added to form a p-type material. The resistance should be R=10 kΩ and handle a current density of $J_{drf}=50$ A/cm^2 when 5 V is applied and have an Ɛ field of less than Ɛ=100 V/m. Design the semiconductor.

8. Consider compensated n-type silicon at T=300 K with a conductivity of σ=16 $(\Omega\text{-cm})^{-1}$ and an acceptor doping concentration of $N_a=10^{17}$ cm^{-3}.

9. Determine the carrier density gradient to produce a given diffusion current density. The hole concentration in silicon at T=300 K varies linearly from x=0 to x=0.01 cm. The hole diffusion coefficient is $D_p=10$ cm^2/s, the hole diffusion current density is $J_{drf}=20$ A/cm^2 and the hole concentration at x=0 is $\rho=4\text{x}10^{17}$ cm^{-3}. Determine the hole concentration at x=0.01 cm

10. Assume that, in an n-type GaAs semiconductor at T=300 K, the electron concentration varies linearly from $1\text{x}10^{18}$ to $7\text{x}10^{17}$ cm^{-3}over a distance of 0.1 cm. Calculate the magnitude of the diffusion current density if the difference coefficient is $D_n=225$ cm^2/s

11. Determine the diffusion coefficient for a carrier mobility of μ=1200 cm^2/V-s at T=300 K

12. For a semiconductor with a diffusion coefficient of D=210 cm^2/s, determine the carrier mobility.

<u>Problem 1</u>: Intrinsic semiconductor

Refer to the plot of intrinsic carrier concentration (n_i) *vs.* absolute temperature (*T*) in the Lecture Notes:

a) Explain qualitatively the differences in intrinsic carrier concentrations for Ge, Si and GaAs. (Why is n_i highest for Ge? Why is it lowest for GaAs?)

b) Explain qualitatively why n_i increases with increasing temperature.

<u>Problem 2</u>: Doping

a) Consider the two-dimensional representation of the semiconductor GaAs shown below:

```
 ••    ••   ••
:As : Ga : As :
 ••    ••   ••
:Ga : As : Ga :
 ••    ••   ••
: Ga : As : Ga :
  ••    ••   ••
```

If Si atoms are inserted as dopants and exclusively replace Ga atoms in the lattice, will the Si doped GaAs material be n-type or p-type? What if the Si atoms exclusively replace As atoms?

b) Consider a Si sample under equilibrium conditions, doped with boron to a concentration 10^{17} cm^{-3}.

i) At T = 300K, is this material n-type or p-type? What are the majority and minority carrier concentrations?

ii) As the temperature of this sample is increased, ni will eventually increase to be higher than the dopant concentration, and the sample will become intrinsic ($n \approx p \approx n_i$). Estimate the temperature at which this occurs, by finding the temperature at which n_i be much greater (at least 10× higher) than n and p. (You can use the formula for n_i given in the Lecture Notes, or simply use the plot of n_i *vs.* T.)

<u>Problem 3</u>: Carrier Concentrations and Energy Band Diagram

a) Consider a Si sample maintained at T = 300K under equilibrium conditions, doped with phosphorus to a concentration 1×10^{16} cm^{-3}.

i). What are the electron and hole concentrations (n and p) in this sample? Is the material n type or p-type?

ii). Draw the energy band diagram for this sample. Indicate ($E_c - E_F$) and ($E_F - E_i$) to within 0.01 eV. (Numeric answer required.)

b) Suppose the sample type is converted to the opposite type by counter-doping it with boron, such that $E_i - E_F = 0.30$ eV.

i). What are n and p in the counter-doped sample?

ii). What is the concentration of boron?

<u>Problem 4</u>: Temperature Dependence of carrier densities and Ef

Consider a Si sample doped with arsenic to a concentration 1×10^{15} cm^{-3}.

a) At T = 0K, what are the equilibrium hole and electron concentrations?

b) At T = 300K, what are the equilibrium hole and electron concentrations? Where is the Fermi level located? (Numeric answer required.)

c) At T = 600K, what are the equilibrium hole and electron concentrations? (Use Figure in the Lecture Nodes to determine n_i at 600K.) Where is the Fermi level located? (Numeric answer required.)

d) Explain qualitatively the trend in E_F-E_i with increasing temperature.

Problem 5: Drift

A n-type silicon sample is maintained at room temperature. When an electric field with a strength of 1000V/cm is applied to the sample, the hole velocity is 2×10^5 cm/sec.

a) What is the mobility of an electron in this sample?

b) Calculate the electron and hole concentrations.

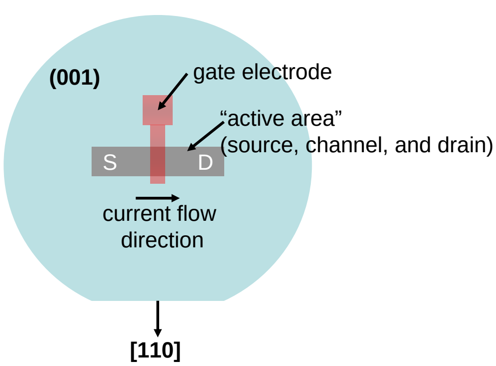
c) Draw the energy band diagram, showing the position of E_F with respect to Ec and Ev.

d) What is the resistivity of this sample?

e) Suppose this sample is used to make an integrated-circuit resistor. The width and height of the sample are 10 µm and 1.5 µm, respectively, and the length of the sample is 20 µm. Calculate the resistance of the sample.

Problem 6: Miller indices

The performance of a MOSFET depends upon the crystalline orientation of the channel surface, as well as the crystalline orientation of the current flow direction. These parameters must be precisely controlled in an integrated-circuit manufacturing process; therefore, silicon wafer substrates are carefully prepared by slicing along (001) planes, and are marked by a "flat" or notch at the edge of the wafer to indicate the [110] direction.
If a MOSFET is laid out on the surface of a (001) silicon wafer as shown in the figure below, what are the Miller indices for the direction of current flow?



Plan view of a MOSFET on a Si wafer

Problem 7: Diamond lattice crystal structure

Germanium (Ge) is a semiconductor material of renewed interest, because it can potentially yield higher MOSFET performance as compared with silicon (Si). Ge atoms are arranged in a diamond lattice structure, as are Si atoms. Given that the lattice constant of Ge is 5.65Å at room temperature (300K), calculate the atomic density of Ge (atoms/cm^3).

Problem 8: Semiconductor doping

(a) Explain why boron (B) is preferred over indium (In) as the dopant species to achieve highly conductive p-type silicon. (hints: The low ionization energy (IE) of boron is 45 meV, whereas that of indium is 160 meV)

(b) At very high temperatures (*e.g.* >1000^{o}C), the conductivity of silicon is not significantly affected by moderate doping (N_A or N_D less than 10^{18}/cm^3), *i.e.* it is an intrinsic semiconductor. Explain why this is the case.

Problem 9: Carrier concentrations

Consider a silicon sample maintained at 300K. Calculate the electron density (n) and hole density (p) for the following cases:

(a) the silicon is undoped
(b) the silicon is doped with 10^{16}/cm^3 boron atoms (all ionized)
(c) the silicon is doped with 10^{16}/cm^3 boron atoms (all ionized) and 10^{17}/cm^3 arsenic atoms (all ionized)

Problem 10: Energy Band Diagram

Consider a Si sample in thermal equilibrium at T = 300K, with electron concentration $n = 1\times10^{18}$ cm^{-3}. Draw the energy band diagram for this sample. Indicate ($E_c - E_F$) and ($E_F - E_i$) to within 0.01 eV.

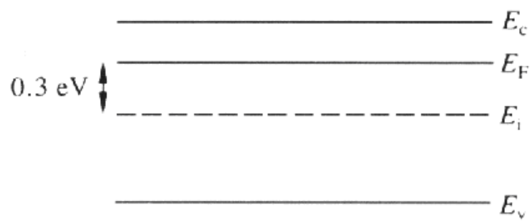
Problem 11: Carrier Mobility and Drift Velocity

A p-type (uncompensated) silicon sample is maintained at 300K. When an electric field with strength 5×10^3 V/cm is applied to the sample, the electron drift velocity is 4×10^6 cm/sec.

a) What is the mobility of this sample?
b) What is the resistivity of this sample?

Problem 12: Fermi Levels

The equilibrium and steady state conditions before and after illumination of a silicon sample maintained at T = 300K are characterized by the energy band diagrams shown below.



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a) What are the equilibrium carrier concentrations n_0 and p_0?

PN Junction

1. Calculate the built in potential barrier of a silicon pn junction at T=300 K with doping concentrations of N_a=2x10^6 cm^{-3} and N_d=5x10^{15} cm^{-3}

2. Repeat question 1 for carrier concentrations of
   i) N_a=5x10^{17} cm^{-3} and N_d=10^{16} cm^{-3}
   ii) N_a=10^{15} cm^{-3} and N_d=2x10^{16} cm^{-3}

3. Calculate the space charge widths and peak electric field in a silicon pn junction at T=300 K with uniform doping concentrations of N_a=2x10^{16} cm^{-3} and N_d=5x10^{15} cm^{-3}, find x_n, x_p, W and $|\mathcal{E}_{max}|$

4. A silicon pn junction at T=300 K with zero applied bias has doping concentrations of N_a=5x10^{16} cm^{-3} and N_d=5x10^{15} cm^{-3}, find x_n, x_p, W and $|\mathcal{E}_{max}|$.

5. Calculate the width of the space charge region in a silicon pn junction with uniform doping concentrations N_a=2x10^{16} cm^{-3} and N_d=5x10^{15} cm^{-3}at T=300 K when a reverse-bias voltage of V_R=5 V is applied

6. A silicon pn junction at T=300 K is reverse biased at V_R=8 V and has doping concentrations of N_a=5x10^{15} cm^{-3} and N_d=5x10^{16} cm^{-3}, find x_n, x_p, W, repeat for V_R=12 V

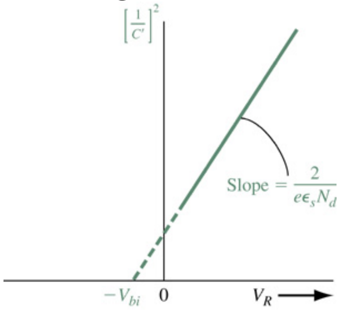
7. Determine the n-type doping required in a silicon pn junction to operate at T=300 K with a p-type doping concentration of N_a=10^{18} cm^{-3} such that the maximum electric field in the space charge region is $|\mathcal{E}_{max}|$=10^5 V/cm at a reverse bias voltage of V_R=10 V.

8. Determine the maximum electric field in a pn silicon with doping concentrations of N_a=5x10^{15} cm^{-3} and N_d=5x10^{16} cm^{-3}, for reverse bias voltages of V_R=8 V and V_R=12 V.

9. Calculate the junction capacitance of a pn junction at V_R=5 V assuming the cross sectional area of the pn junction is A=10^{-4} cm^2.

10. Consider a GaAs pn junction at T=300 K doped at concentrations of N_a=1x10^{15} cm^{-3} and N_d=2x10^{16} cm^{-3} and with a junction area of A=10^{-4} cm^2 when the reverse bias voltage is V_R=0 V and V_R=5 V.

11. Determine the impurity concentrations in a p^+n junction at T=300 K, assuming the intercept on the voltage axis of the curve below gives v_{bi}=0.742 V and that the slope is 3.92×10^{15} $(F/cm^2)^{-2}/V$



12. The experimentally measured junction capacitance of a one sided p^+n silicon junction biased at V_R=4 V at T=300 K is C=1.10 pF. The built in potential barrier is found to be v_{bi}=0.782 V The cross-sectional area is $A=10^{-4}$ cm^2. Find the doping concentrations.

<u>Problem 1</u>: pn Junction Electrostatics

a) A pn step junction is made in silicon with $N_A = 5\times10^{16}$ cm^{-3} and $N_D = 1\times10^{16}$ cm^{-3}. Assume T = 300K. Calculate the following:
i) the built-in potential *V*bi
ii) the depletion layer width *W* at zero bias
iii) the maximum electric field at zero bias
iv) the maximum electric field at 5V reverse bias

b) Sketch the energy band diagram, charge density distribution, electric field distribution, and potential distribution as a function of position *x* for both zero bias and 5V reverse bias.

<u>Problem 2</u>: pn Junction Electrostatics

A silicon step junction maintained at T = 300K under equilibrium conditions has a p-side doping of $N_A = 1\times10^{16}$ cm^{-3} and n-side doping of $N_D = 1\times10^{15}$ cm^{-3}.

a) Calculate the built-in voltage, V_{bi} (sometime it is called built-in potential V_0 or ϕ_B).

b) Calculate the depletion width, *W*. What are x_{po} and x_{no}?

Note that $x_{po} = \frac{N_D}{N_A + N_D}W$ and $x_{no} = \frac{N_A}{N_A + N_D}W$

c) What is the electrostatic potential at x = 0, *i.e.* how much voltage is dropped across the p-side?

Note that $V(0) = \frac{qN_A}{2\varepsilon_s}x_{po}^2 = V_{bi} - \frac{qN_D}{2\varepsilon_s}x_{no}^2$

d) Calculate the peak electric field (at x = 0): $E(0) = -\frac{2V_{bi}}{W}$

e) Sketch (roughly to scale) the charge density distribution $\rho(x)$, electric field distribution $\varepsilon(x)$, and electrostatic potential $V(x)$.

MOS Fundamentals

1. Determine the potential φ_{Fp} in silicon at T=300 K for a) $N_a=10^{15}$ cm^{-3} and b) $N_a=10^{17}$ cm^{-3}

2. Consider p-type silicon at T=300 K. Determine the doping concentration if φ_{Fp}=-0.34 V

3. Calculate the maximum space charge width for silicon at T=300 K doped to $N_a=10^{16}$ cm^{-3}

4. Consider an oxide-to-p-type silicon junction at T=300 K. The impurity doping concentration in the silicon is $N_a=3x10^{16}$ cm^{-3}, calculate the maximum space charge width in the silicon. Repeat for an impurity concentration of $N_a=10^{15}$ cm^{-3}.

5. Calculate the metal semiconductor work function difference φ_{ms}. For an aluminium-silicon dioxide junction φ'_m = 3.2 V and for a silicon-silicon dioxide junction χ'=3.25 V. Assume that E_G=1.12 eV and let the p-type doping be $N_a=10^{14}$ cm^{-3}

6. Calculate the metal-semiconductor work function difference φ_{ms} for an aluminium-silicon dioxide-silicon device if the silicon is doped to a concentration of $N_a=10^{16}$ cm^{-3}. Assume T=300 K

7. Calculate C_{ox}, C'_{min}, C'_{FB} for an MOS capacitor. Consider a p-type silicon substrate at T=300 K doped to $N_a=10^{16}$ cm^{-3}. The oxide is silicon dioxide with a thickness of 550Å and the gate is aluminium.

8. Consider an MOS device with the following parameters. Aluminium gate, p-type substrate, $N_a=3x10^{16}$ cm^{-3}, t_{ox}=250Å and $Q'_{ss}=10^{11}$ cm-^{2}. Determine C'_{min}/C_{ox} and C'_{FB}/C_{ox}.

Problem 1: MOS Fundamentals

Consider an ideal MOS capacitor maintained at T = 300K with the following characteristics:

- Gate material is p+ polycrystalline-silicon (work function Φ_M = 5.15eV)
- Substrate is n-type Si, with doping concentration $10^{18}cm^{-3}$
- Oxide thickness x_o = 2 nm

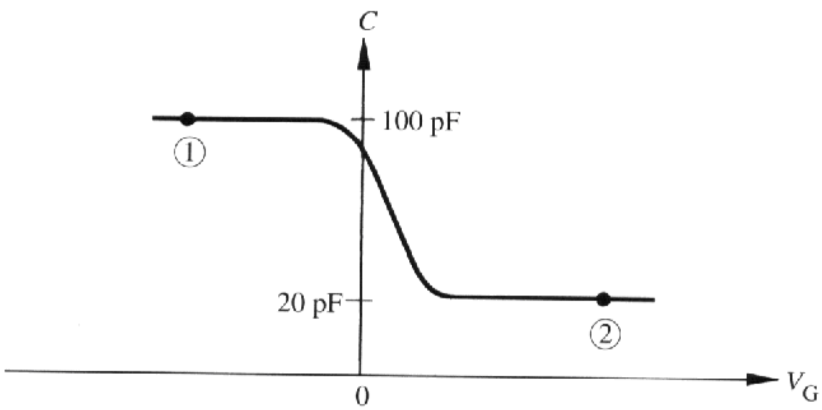
a) What is the flat-band voltage, V_{FB}, of this capacitor?

b) Sketch the energy-band diagrams, labeling qV_G, $q\phi_S$, qV_{ox} (no numerical values required), for the following bias conditions:

i) flat-band
ii) accumulation
iii) equilibrium
iv) strong inversion

Problem 2: MOS Capacitance

The capacitance *vs.* gate voltage characteristic of a simple MOS capacitor of area 1×10^{-4} cm^2 is as shown:



a) Is the semiconductor (silicon) substrate doped n-type or p-type? Explain briefly.

b) Sketch the block charge density diagrams corresponding to points (1) and (2) on the *C-V* characteristic.

c) What is the thickness of the gate oxide (SiO_2), x_o?

d) What is the semiconductor doping concentration?

e) Is the measurement frequency low or high? Explain briefly.

f) Indicate qualitatively how the *C-V* characteristic would change if the semiconductor doping concentration were to be increased.

Problem 3: MOS Capacitance

An MOS capacitor is made on uniformly doped p type material. With -20V on the gate with respect to the substrate it has a capacitance of 20pF. With +20V on the gate it has a capacitance of 10pF. What is the thickness of the depletion layer and the also the oxide if the capacitor has an area of 10^{-6}m^2.

MOSFETs and IC's

1. Design the width of a MOSFET such that a specified current is induced for a given bias. Consider an ideal n-channel MOSFET with parameters L=1.25 μm, μ_n=650 cm^2/V-s, C_{ox}=6.9x10^{-8} F/cm^2 and V_T=0.65 V. Design the channel W such that I_D(sat)=4 mA for V_{GS}=5 V

2. The parameters of an n-channel MOSFET are μ_n=650 cm^2/V-s, t_{ox}=200 Å, W/L=50 and V_T=0.4 V. If the transistor is biased in the saturation region find the drain current for V_{GS}=1, 2, 3 V

3. Consider an n-channel MOSFET with W=15 μm, L=2 μm, C_{ox}=6.9x10^{-8} F/cm^2. Assume a drain current in the nonsaturation region for V_{DS}=0.1 V is I_D=35 μA at V_{GS}=1.5 V and I_D=75 μA at V_{GS}=2.5 V. Determine the inversion carrier mobility from experimental results.

4. Consider the n-channel MOSFET in Question 3. Using the results in the example, determine the threshold voltage of the MOSFET.

5. Consider a p-channel MOSFET with parameters μ_p=300 cm^2/V-s, C_{ox}=6.9x10^{-8} F/cm^2, W/L=10 and V_{TP}=-0.65 V. Determine the conduction parameter β and find the maximum current at V_{SG}=3 V

6. The maximum current in a p-channel MOSFET must be I_D=0.85 mA at V_{SG}=3 V. If the transistor has the same electrical parameters as in question 5. Determine the required width to length ratio.

Problem 1: The MOSFET as a Resistor

Calculate the resistance of a load MOST with an aspect ratio of 1 when the mobility of the electrons is 1000$cm^2V^{-1}sec^{-1}$ and the gate capacitance per unit area is $10^{-2}Fm^{-2}$. The drain voltage is V_{DD}=5V and the threshold voltage V_T= 0.5V. (Hints: In this case the gate and the drain are connected together so that V_G=V_D.)

Problem 2: The nMOS logics

Calculate W/L with the given specification (see two examples on lecture "nMOS logic IC design").

Problem 3: The micro fabrication

Describe the fabrication of an IC resistor, a pn junction, and an nMOSFET using planar technology.