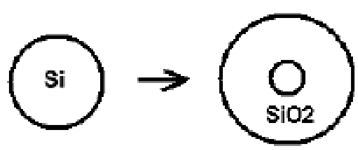
Problem 1: Deep level traps and carrier concentration (40 points)
Cu or Au impurities introduce allowed energy states deep within the forbidden gap of silicon. Assume that each defect introduces two discrete levels: an acceptor level 0.51 eV above the top of the valence band and a donor level 0.27 eV above the top of the valence band. (Note that $E_a > E_d$, and that these are not shallow levels.) The ratio of the number of defects with each charge state (+, - , or neutral) at thermal equilibrium is given by the relation

$$N_d^+ : N_0 : N_a^- = \exp\frac{E_d - E_f}{kT} : 1 : \exp\frac{E_f - E_a}{kT}$$

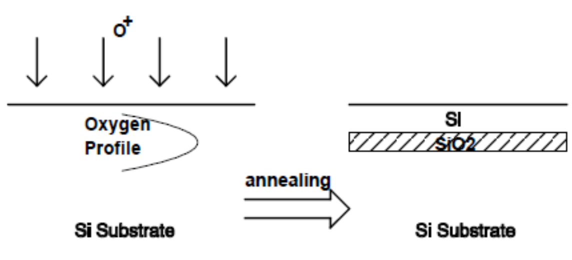
Ef is adjustable with the addition of dopants (shallow defects).

(a) Sketch the densities of these three species as the Fermi level moves from Ev to Ec. Which species dominates in heavily doped p-type material? In n-type material?
(b) What is the effect of the defects on the majority-carrier concentrations?
(c) Using the above information, determine the charge state of the defect levels and the position of the Fermi level in a silicon crystal containing no shallow dopant atoms. Is the sample p- or n-type? (Hint: p and n are very small).
(d) What are the electron and hole concentrations and the location of the Fermi level in a sample with 2 $\times10^{17}$cm^{-3} phosphorus atoms and 5 $\times10^{16}$ cm^{-3} defects?

Problem 2: Si consumed during thermal oxidation (10 points)
Pure Si contains 5×10^{22} Si atoms per cm^3 and SiO_2 contains 2.3×10^{22} SiO_2 molecules per cm^3. A long cylindrical Si rod of radius 100nm is oxidized and a 100nm-thick SiO2 sheath is formed. What is the radius of Si region in the middle? Assume cylindrical symmetry is maintained during thermal oxidation and ignore any effects caused by stress. (This Si consumption technique is one method to fabricate silicon nanowires down to 10nm in diameter. In reality, large stress produced in the silicon rod oxidation changes the oxidation rate and volume)



Problem 3: Silicon-on-insulator (SOI) Substrate formation (30 points)
Separation by Implantation of Oxygen (SIMOX) is one method of forming Si on Insulator (SOI) substrates. Oxygen ions are implanted deep below the Si surface with a high dose. The as-implanted oxygen depth profile is approximately Gaussian. With a high temperature post-implantation annealing step (> 1200°C), the implanted oxygen atoms will coalesce to form a continuous buried layer of pure SiO_2.



(a) What is the oxygen ion dose (in O atoms/cm^2) required to form a buried SiO2 layer 0.1 um thick? [Hint: To get the dose required, you only have to know the oxygen concentration of SiO2 and its final thickness. Molecular density of SiO2 is 2.3 $\times10^{22}$ molecules/cm^3.].

(b) Calculate the required implantation time to implant a 200mm-diameter Si wafer if the beam current is 10mA? Assume the ion beam is rastering a 20cm x 20cm square area.
(c) To position the oxygen profile deep below the wafer surface, an accelerating voltage of 200kV is used. Calculate the power (= voltage × current) supplied by the ion beam to the Si wafer. If this power is converted to heat, comment on temperature of the Si wafer during the implantation.

Problem 4: Mobility and resistance (20 points)
Find the mobility of electrons in aluminum with resistivity 2.8 x 10^{-6} Ωcm and density 2.7 g cm^{-3}. The atomic weight of aluminum is 27. Of the three valence electrons in aluminum, on the average 0.9 electrons are free to participate in conduction at room temperature. If effective mass m^* = electron mass m_0 (9.11E-31 kg) find the mean time between collisions and compare this value to the corresponding value in lightly doped silicon, where $m^*(Si)=0.26m_0$, and effective mobility is 1420 cm^2/Vs.