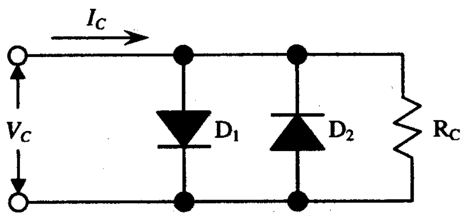
Student #:____________________

1. A "clipper" circuit can be built by using a parallel combination of two diodes and a resistor, as shown below.

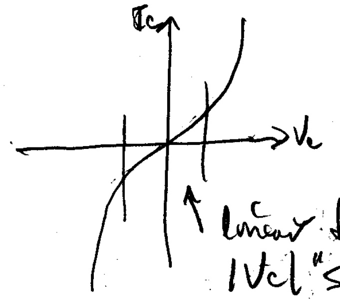


a) Assuming the two diodes, D_1 and D_2 can be considered to be ideal and identical, derive an expression for the I_C versus V_C relationship for the circuit.

$$I_c = I_{D1} + I_{D2} + I_{Rc}$$
$$= I_s(e^{\frac{qV_c}{kT}}-1) - I_s(e^{-\frac{qV_c}{kT}}-1) + \frac{V_c}{R_c}$$
$$= I_s(e^{\frac{qV_c}{kT}} - e^{-\frac{qV_c}{kT}}) + \frac{V_c}{R_c}$$
$$= I_s 2\sinh\left(\frac{qV_c}{kT}\right) + \frac{V_c}{R_c}$$

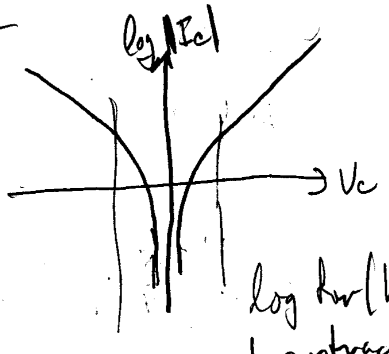
b) Sketch the resulting *I-V* characteristic using appropriate linear and logarithmic scales and indicate the regions over which each type of plotting might be best used.

Linear



linear for $|V_c|$ "small" to extract R_c

Log



log for $|V_c|$ "large" to extract $\frac{q}{kT}$

$\sinh x \approx x$ for $|x| << 1$

$\Rightarrow I_c \approx \left(\frac{2q}{kT}I_s + \frac{1}{R_c}\right)V_c$ for $-kT << qV_c << kT$

Optional

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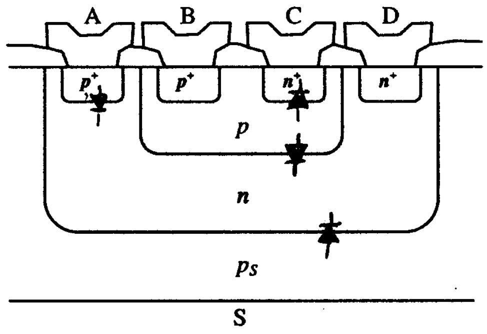
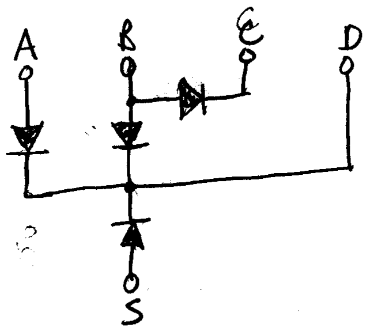
2. We wish to fabricate a structure in silicon with the cross-section shown below.



a) Assuming all the *PN* junctions act as isolated diodes and ignoring parasitic resistances, draw the equivalent circuit for this structure in terms of the contacts A, B, C, D and the substrate S. (i.e. draw how the diodes are connected to each other and A, B, C, D and S.)



b) How many mask-levels (i.e. patterning steps) are required to fabricate this structure (including metal) and which features of the structure are defined by each mask? (In the order in which they are processed.)

Six mask-level are required.

1) n-well in substrate

2) p-well in n-well.

either way

3) p+ implants in p-and n-wells

4) n+ implants in p-and n-wells

5) cuts in contact insulator layer

6) metalization patterning

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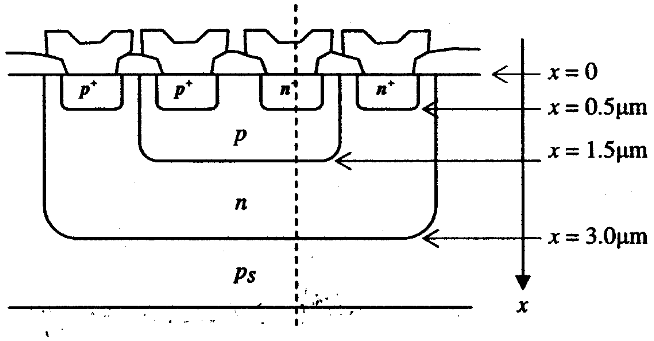
3. Consider a structure fabricated in silicon with the cross-section shown below.



a) The starting substrate has a doping of $p_s = 10^{14}$ cm^{-3}, the implant to form the n-region is $N_D = 5\text{x}10^{14}$ cm^{-3}, for the p-region it is $N_A = 10^{15}$ cm^{-3}, the n$^+$-region is $N_D{}^+ = 10^{18}$ cm^{-3} and the p^+-region is $N_A{}^+ = 5\text{x}10^{17}$ cm^{-3}. Calculate the carrier densities n, p, p^+ and n^+.

$n = N_D - p_s = 4\times10^{14}\,cm^{-3}$

$p = N_A - n = 10^{15} - 4\times10^{14} = 6\times10^{14}\,cm^{-3}$

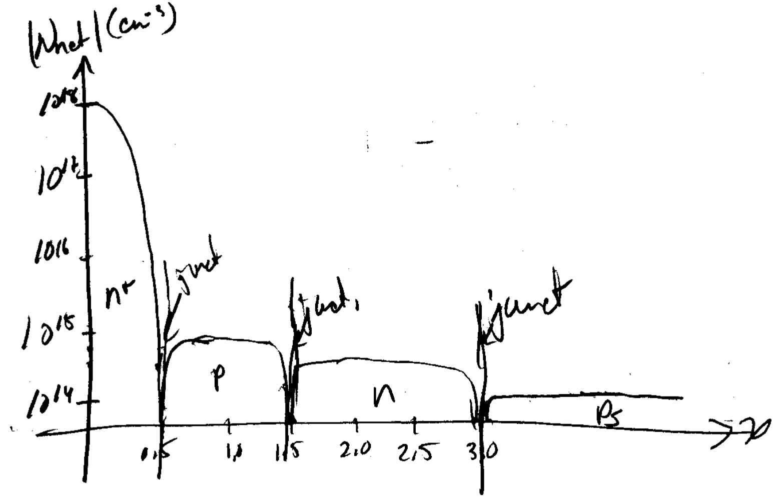
$p^+(\text{in } n) = N_A^+ - n = 5\times10^{17} - 4\times10^{14} \simeq 5\times10^{17}\,cm^{-3}$

$n^+(\text{in } n) = N_D^+ + n = 10^{18} + 4\times10^{14} \simeq 10^{18}\,cm^{-3}$

$p^+(\text{in } p) = N_A^+ + p = 5\times10^{17} + 6\times10^{14} \simeq 5\times10^{17}\,cm^{-3}$

$n^+(\text{in } p) = N_D^+ - p = 10^{18} - 6\times10^{14} \simeq 10^{18}\,cm^{-3}$

b) Sketch a plot of the one-dimensional doping profile for this structure at the dashed line on a log-linear scale and indicate the positions of the junctions.



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4. A material has a net valence of 4 (i.e it is Group IV or an equal combination of Group III and Group V, etc.) and forms a crystal bonded in a diamond type lattice. The material has a bandgap of $E_g = 3.4$eV.

a) Would this material be considered to be a metal, semi-metal, semiconductor or insulator? Explain your choice.

Since the bandgap is large (>3eV) this could be considered an insulator. It is close to the limit though so it may also act as a semiconductor.

b) The intrinsic carrier concentration for this material is $n_i = 2.0\text{x}10^{-10}$ cm^{-3}. What is the doping concentration required to obtain a minority carrier density of 1 cm^{-3} in this material?

To calculate the equilibrium carrier densities we use the Mass Action Law. For n-type doping:

$$N_D p = n_i^2 \Rightarrow N_D = \frac{n_i^2}{p} = \frac{4.0\times10^{-20}}{1} = 4.0\times10^{-20}\ \text{cm}^{-3}$$

But this is << ni!

∴ it is not possible to obtain this high of a minority carrier distribution in equilibrium.

c) If the bandgap of the material were reduced, with all other conditions remaining the same, would n_i get larger or smaller? Explain your answer.

If the bandgap was smaller ni would be larger. This is because the intrinsic carrier density is the density of electrons excited from the valence band to the conduction band by thermal energy. The smaller Eg the larger the proportion of carriers that will have sufficient energy.

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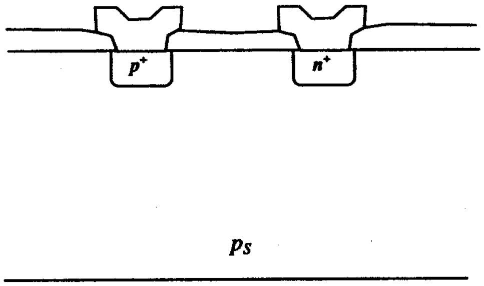
5. We can fabricate a lateral diode on the surface of a silicon wafer as shown below.



a) Outline the process steps required to fabricate this structure.

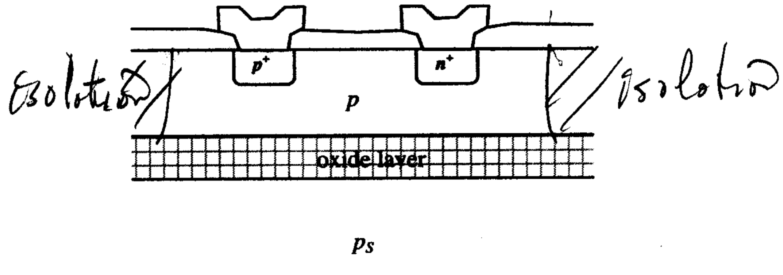
Apply PR
Pattern for p^+ and develop
Implant p^+
Strip PR
Repeat for n^+ implant
Deposit insulator layer

Apply PR
Pattern for contact cut and develop
Etch contact holes
Strip resist
Deposit metalization
Repeat for metal patterning

b) Why would such a structure normally be unacceptable for practical use in integrated circuits?

There is no isolation from other devices or the substrate

c) If we built this structure on a silicon-on-insulator substrate, as shown below, what additional process step(s) would be necessary to make it useful in an integrated circuit?



The device needs to be isolated.
Could use: 1) Implant to form reverse biased junctions
2) Trenches etched to oxide layer
3) Thick thermal oxide extending down to oxide layer.

6. **When a shallow surface implant or deposition of dopant is used followed by a thermal diffusion step we usually assume the resulting doping profile is Gaussian. This can be modeled by the equation below for donor diffusion.**

$$N_D(x) = N_{D0} e^{-\frac{x^2}{2\sigma^2}}$$

a) **If the substrate is initially doped at $N_A = 10^{15}$ cm^{-3} find the value of the surface donor concentration, N_{D0}, required to get a metallurgical junction depth of $x = 2\mu m$ for $\sigma = 1\mu m$.**

$$N_D(x) = N_A = N_{D0}\, e^{-\frac{x^2}{2\sigma^2}}$$

$$\Rightarrow N_{D0} = 10^{15} e^{\frac{4}{2}} = e^2 \times 10^{15} \approx 7.4 \times 10^{15}\ cm^{-3}$$

b) **Calculate the total "dose" (total number per cm^2) of donor atoms implanted to give this profile.**

$$D_G = \int_0^{\infty} N_D(x)\, dx = N_{D0} \int_0^{\infty} e^{-\frac{x^2}{2\sigma^2}} dx = N_{D0} \sqrt{\frac{\pi}{2}}\, \sigma = 7.4 \times 10^{15} \sqrt{\frac{\pi}{2}}\, 10^{-4}$$

$$\approx 9.3 \times 10^{11}\ cm^{-2}$$

c) **Using the uniform doping approximation instead of the Gaussian again calculate the total "dose", in cm^{-2}, of donor atoms implanted.**

$$D_u = N_{D0}\, x = 7.4 \times 10^{15} \cdot 2 \times 10^{-4} \approx 1.48 \times 10^{12}\ cm^{-2}$$

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7. One of the most important concepts in the theory of semiconductors is the Mass-Action Law.

a) Write down the Mass-Action Law equation and define all the variables. Under what conditions is the Mass-Action Law valid?

$np = n_i^2$

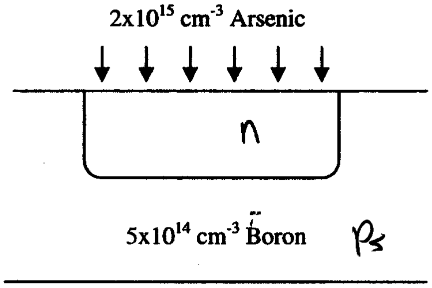
n - concentration of electrons in cm^{-3}

p - concentration of holes in cm^{-3}

n_i - intrinsic concentration of electrons or holes

Valid for intrinsic and doped material in equilibrium.

b) A silicon substrate that has been doped to a level of 5×10^{14} cm^{-3} of Boron (type III dopant) is implanted with 2×10^{15} cm^{-3} of Arsenic (type V dopant), as shown below. Calculate the resulting concentrations of both majority and minority carriers in the substrate and implanted regions indicating in each case the type of carrier (electron or hole).



Type III is an acceptor so for the substrate:

Majority Carriers - $P_s = N_A = 5\times10^{14} cm^{-3}$ holes

Minority Carriers $n_s = \frac{n_i^2}{P_s} = \frac{(1.45\times10^{10})^2}{5\times10^{14}} = 4.2\times10^5 cm^{-3}$ electrons

Type V is a donor so for the implanted region:

Majority carriers - $n = (N_D - P_s) = 1.5\times10^{15} cm^{-3}$ electrons

Minority carriers - $p = \frac{n_i^2}{n} = \frac{(1.45\times10^{10})^2}{1.5\times10^{15}} = 1.4\times10^5 cm^{-3}$ holes

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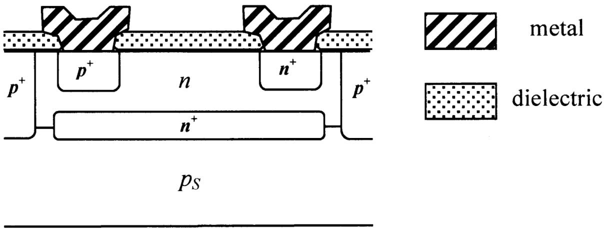
8. A silicon diode is fabricated with the cross section shown in the diagram below.



a) What type of diode is this?

Epitaxial diode

b) What are the patterning (or mask) steps required to fabricate this diode? (In the order of fabrication.)

1) n+ buried region definition
2) p+ isolation implants
either way 3) n+ contact implant
4) p+ contact implant
5) contact cuts in dielectric
6) metal pattern

Note: theoretically the p+-isolation could follow the contact implants if deep diffusion wasn't required

c) The p^+ contact implant has dimensions of 3 μm (3×10^{-4} cm) by 10 μm (10^{-3} cm) perpendicular to the current flow of $I_D = 20$ mA through this diode, as shown. What is the current density through the junction, J_D?

$$J_D = \frac{I_D}{A_D}$$
$$= \frac{20\times10^{-3}}{3\times10^{-4}\cdot 10^{-3}}$$
$$= 6.67\times10^{4}\ A/cm^2$$