Name:____________________
Student Number:____________________

ELEC 3908 – Physical Electronics

Quiz #1
Practice Problem Set

? Minutes

January 22, 2016

- No aids except a non-programmable calculator
- All questions must be answered
- All questions have equal weight
- Answer questions on quiz sheets (use backs if necessary)
- Write your student number at the top of each page

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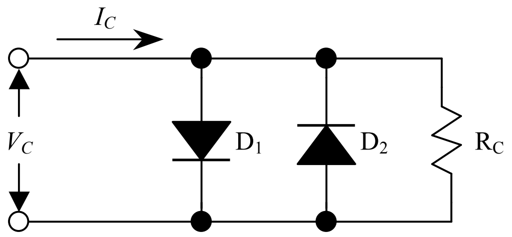
1. A "clipper" circuit can be built by using a parallel combination of two diodes and a resistor, as shown below.



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.

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.

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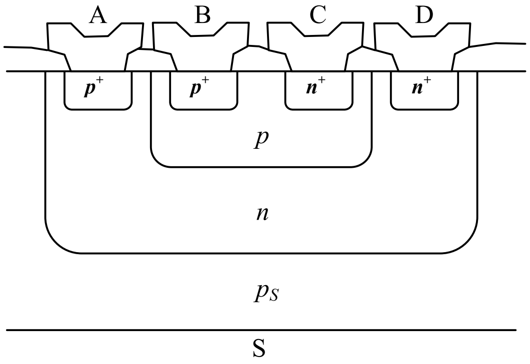
2. We wish to fabricate a structure in silicon with the cross-section shown below.



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.)

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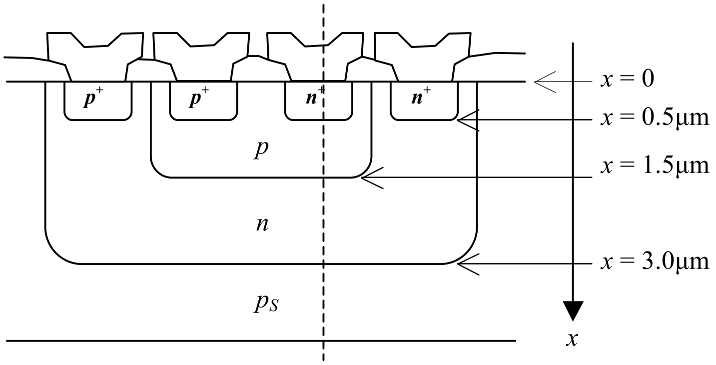
3. Consider a structure fabricated in silicon with the cross-section shown below.



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^+.

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 metalurgical 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 $E_g = 3.4\text{eV}$.

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

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

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.

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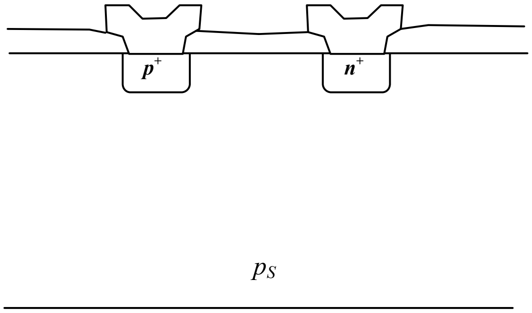
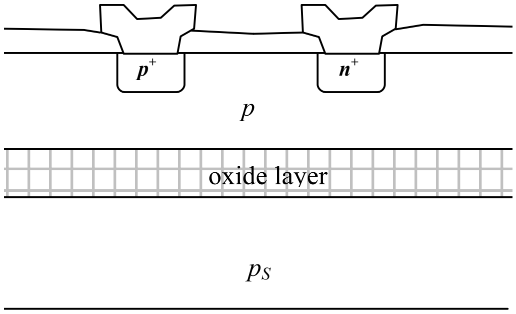
5. We can fabricate a lateral diode on the surface of a silicon wafer as shown below.



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

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

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



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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 $x = 2$µm for $\sigma = 1$µm.

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

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

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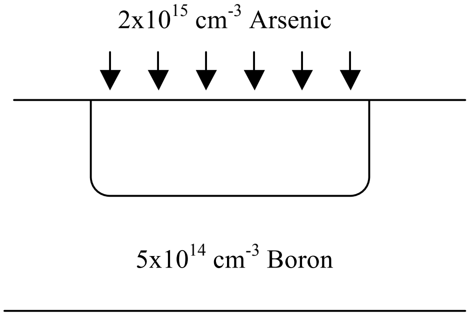
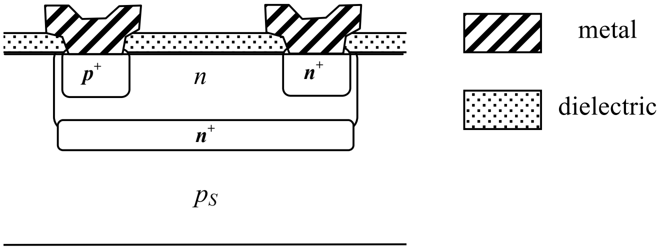
7. One of the most important concepts in the theory of semiconductors is the Mass-Action Law.

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

   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).



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



a) What type of diode is this?

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

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

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9. We have come across diffusion in two contexts so far in this course.

a) What is diffusion?

b) What causes diffusion?

c) What are the two types of diffusion that we have studied and what are the main differences between them?

d) Write down the general equation describing diffusion in one-dimension. How is this changed to find the diffusion current density?

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10. The Shockley-Read-Hall model uses the equation below to calculate the net recombination rate in a semiconductor.

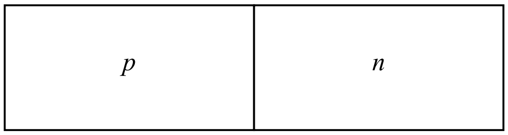
$$U = \frac{n(x)p(x) - n_i^2}{\tau_0\left(n(x) + p(x) + 2n_i\right)}$$

a) Under the conditions of low-level injection in a p-type material $n_{p0} << n(x) << p(x)$. How can we simplify the expression for U_p under these conditions.

b) In the approximation found in (a) U_p is a rate of change of carriers. Write down the equivalent differential equation and solve it to obtain Δn as a function of t.

c) If the minority carrier concentration in a *p*-type material is initially raised by Δn_0 under low-injection conditions how long will it take the excess carrier concentration to fall to $\Delta n_0/2$ if the minority carrier lifetime is $\tau_0 = 10^{-6}$ sec?

11. Imagine an interface is formed instantaneously between p-type and n-type regions of silicon as shown below.



a) What two forces acting on the carriers need to balance to bring the carriers in the junction region to equilibrium?

b) If the net doping of the diode is $N_A = 2\text{x}10^{16}$ cm^{-3} and $N_D = 5\text{x}10^{16}$ cm^{-3} and the junction is far away from the contacts (>> L_n, L_p) calculate the total saturation current density, J_S, for $\tau_0 = 10^{-6}$ sec and $T = 300$K. (Use the attached sheets for any required constants and equations.)

c) If the effective area of the diode is 2µm x 5µm ($2\text{x}10^{-6}$m x $5\text{x}10^{-6}$m) and it has negligible series resistance, what would the junction voltage, V_D, be for a diode current of $I_D = 10$ mA.

Equations

Ideal Diode: $I_D = I_S\left(e^{qV_D/kT} - 1\right)$

Shockley-Reed-Hall: $U = \dfrac{n(x)p(x) - n_i^2}{\tau_0\left(n(x) + p(x) + 2n_i\right)}$

Einstein Relations: $D_n \equiv \dfrac{kT}{q}\mu_n, \quad D_p \equiv \dfrac{kT}{q}\mu_p$

Diffusion Length: $L_n \equiv \sqrt{D_n\tau_0}, \quad L_p \equiv \sqrt{D_p\tau_0}$

Saturation Current Density:

$$J_S = \frac{qD_n n_{p0}}{L_n} + \frac{qD_p p_{n0}}{L_p}, \quad \text{for } pn \text{ junction (thick p and n)}$$

$$J_S = \frac{qD_n n_{p0}}{w_p} + \frac{qD_p p_{n0}}{L_p}, \quad \text{for } p^+n \text{ junction (thin p}^+\text{)}$$

$$J_S = \frac{qD_p p_{n0}}{w_n} + \frac{qD_n n_{p0}}{L_n}, \quad \text{for } n^+p \text{ junction (thin n}^+\text{)}$$

Gaussian Integral: $\displaystyle\int_0^\infty e^{-\frac{x^2}{2\sigma^2}}dx = \sqrt{\frac{\pi}{2}}\sigma$

Hyperbolic Sine: $\sinh(x) = \dfrac{e^x - e^{-x}}{2}$

Hyperbolic Cosine: $\cosh(x) = \dfrac{e^x + e^{-x}}{2}$

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Physical Constants and Material Properties

Quantity	Symbol	Value
Micron	μm	10^{-4} cm = 10^{-6} m
Angstrom Unit	Å	10^{-8} cm = 10^{-10} m
Boltzmann's Constant	k	8.62×10^{-5} eV/K
		1.381×10^{-23} J/K
Electronic Charge	q	1.602×10^{-19} C
Electron Volt	eV	1.602×10^{-19} J
Electron Rest Mass	m_o	9.11×10^{-31} kg
Free Space Permittivity	ε_o	8.854×10^{-14} F/cm
Plank's Constant	h	6.626×10^{-34} J-s
		4.14×10^{-15} eV-s
Thermal Voltage at 300K	kT/q	0.02586 V

Properties of Silicon at 300K

Quantity	Symbol	Value
Intrinsic Carrier Concentration	n_i	1.45×10^{10} cm^{-3}
Effective Densities of States	N_v	1.08×10^{19} cm^{-3}
	N_c	2.8×10^{19} cm^{-3}
Electron Affinity	χ^{Si}	4.05 eV
Energy Gap	E_g	1.08 eV
Bulk Electron Mobility	μ_n	1350 cm^2/V-s
Bulk Hole Mobility	μ_p	470 cm^2/V-s
Surface Electron Mobility	$\overline{\mu_n}$	520 cm^2/V-s
Permittivity	ε_{Si}	$11.7\varepsilon_o$

Properties of Silicon Dioxide

Quantity	Symbol	Value
Permittivity	ε_{ox}	$3.9\varepsilon_o$