Problem 1 of 3 (Answer each question briefly and clearly. (35 points)

What is the mass-action law? (5pts)

└ whole content of EE105

It states that $np=n_i^2(T)$*, or that the product of concentrations of free holes and electrons is a function of temperature.*

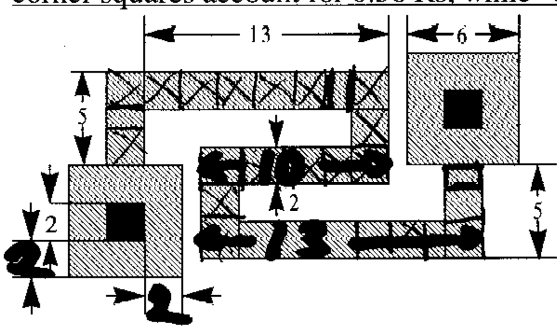
What is the concentration of holes, electrons and ions if Si is doped with 10^{16} As atoms/cm^3, at room temperature? (5pts) n_i :

As is in group VI, it has five valence electrons, so it creates free electrons, while As atoms become positive ions. The concentration of positive ions is 10^{16}*, the concentration of electrons is also* 10^{16}*, while the concentration of holes, at room temp is* 10^4*.*

What are the four types of currents you can find across a p-n junction at equilibrium? (6pts)

electron drift, electron diffusion, hole drift and hole diffusion currents.

Find the resistance of the following structure (drawn to scale), if the Rs is 10 Ohms/square. Assume corner squares account for 0.56 Rs, while "dogbone" contact areas amount to 0.65 squares. (8pts)



0.65+1.5+0.56+5.5+0.56+1+0.56+3+0.56+1+0.56+5.5+0.56+1.5+0.65=1.3+6x0.56+19=23.44, so the total resistance is about 234.4Ohms.

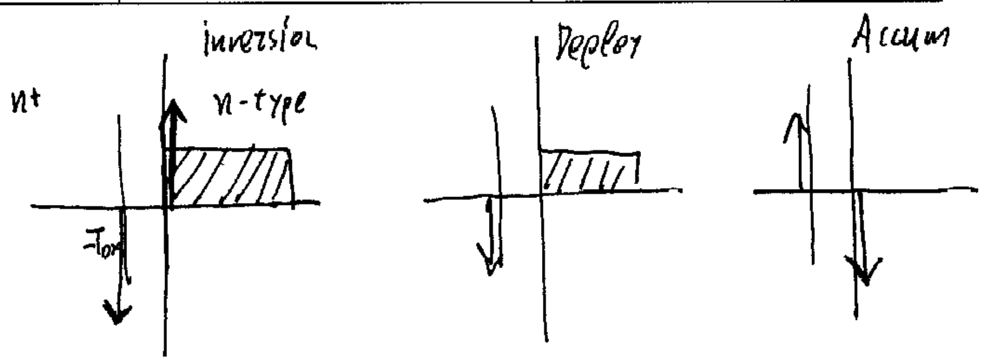
At what gate-to-bulk bias [redacted] do you obtain the *minimum* possible capacitance [redacted] of an MOS structure on top of a p-type substrate? (5pts)

This happens exactly before the point of inversion, when we have the maximum depletion region, but no inversion layer, [redacted]

V_{Tn}

Consider an MOS structure on top of a *n-type* substrate, while using *n+* type gate. Mark the type of charges (i.e. positive ions / negative ions / free electrons / free holes) on the gate and the substrate as a function of the biasing conditions on the following table (6pts):

Bias	Gate Charges	Substrate Charges
Accumulation	*positive ions*	*free electrons*
Depletion	*free electrons*	*positive ions*
Inversion	*free electrons*	*free holes and positive ions*



Problem 2 of 3 (40 points)

Sometimes, a special "Vt-adjust" implant is being used in order to set the threshold volatge of a device at a specific value. The process sequence described next is an example of this. Please follow the steps and draw the two cross sections at the steps indicated (*10 points*):

Step 0: start with 10^{15} atoms/cm^3 p-type wafer and 0.5μm of isolation oxide.

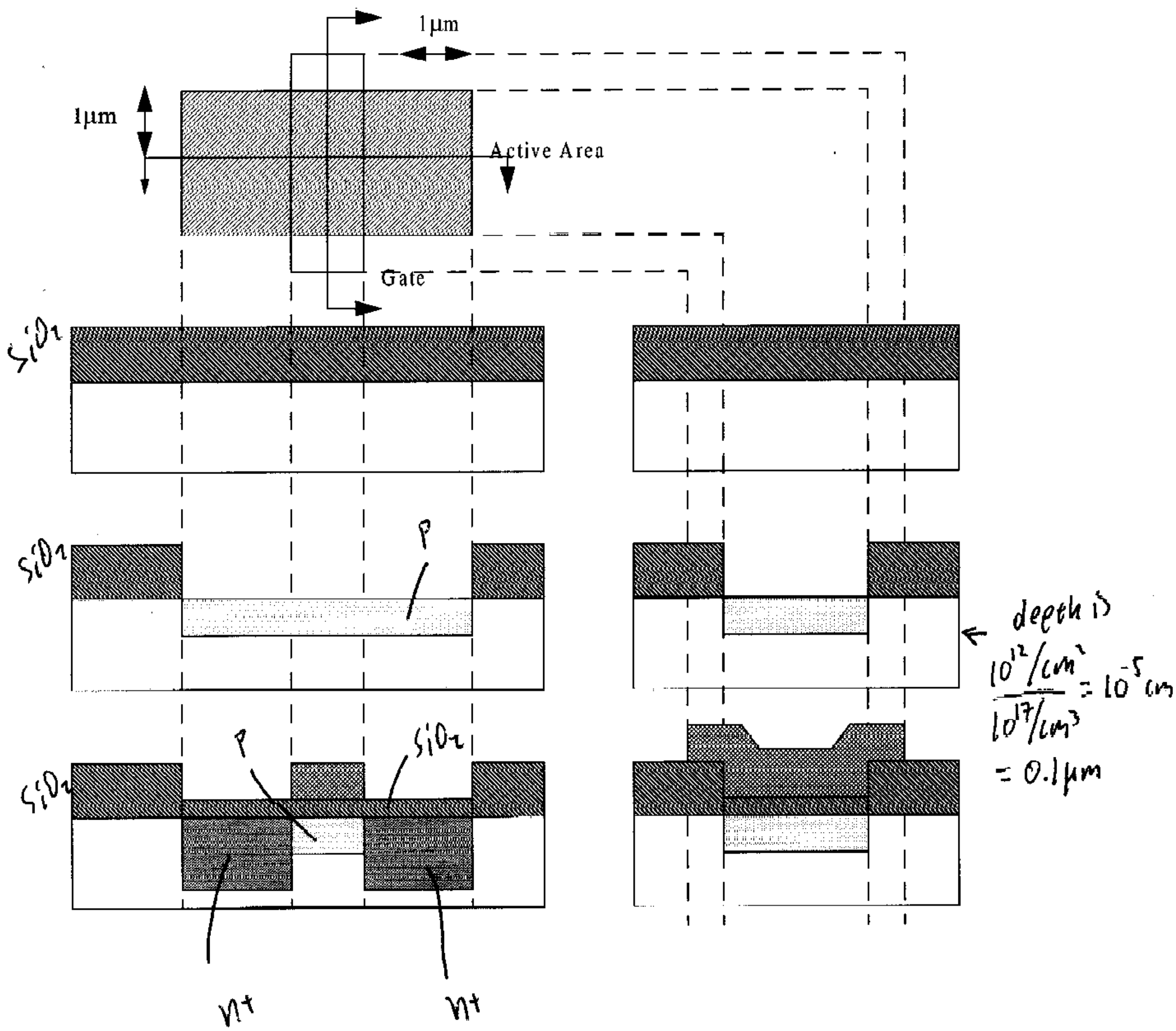
Step 1: use mask shown to create active area (i.e. remove the thick gate oxide in shaded region.)

Step 2: implant a dose of 10^{12} atoms of Boron per cm^2, so that the annealed profile has a uniform concentration of 10^{17}/cm^3 from the surface down to a finite depth. (draw the two cross sections marked on the graph and calculate and mark the depth of the annealed Boron profile.)

Step 3: grow 100Angstroms of gate oxide

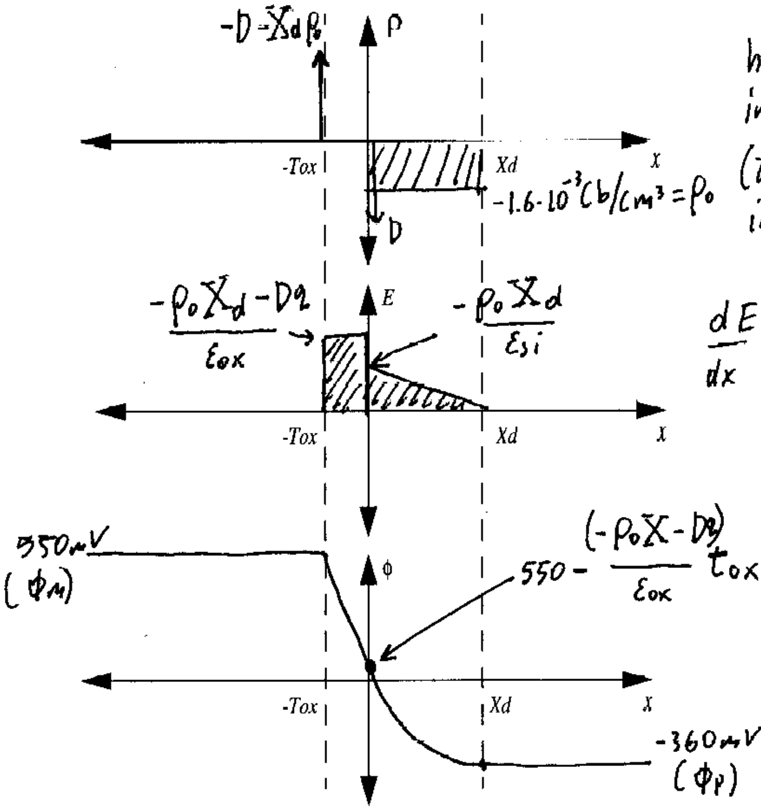
Step 4: deposit and pattern gate

Step 5: Implant n+ source/drain and gate, to a depth of 0.5μm. (draw the two cross sections marked on the graph)



On a different example of using the Vt adjust implant, make the assumption that the implant is very shallow, so all its charge can be approximated by a delta function at the surface of the channel. Now consider the specific case when we have n+ poly (assume ϕ_m=0.55V), p-type substrate with $10^{16}/cm^3$ concentration of Boron, and a Tox of 100Angtsroms (10^{-6} cm). The unknown in this problem is the dose D and the polarity of the implanted material, in # of atoms / cm^2.

Sketch the charge density (ρ), electric field (*E*) and potential (ϕ) diagrams (15 *points*). Label all values with the proper symbolic expression.



here I assume D is negative, i.e. the implant is made of acceptors (this assumption will be resolved in the numerical solution next)

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

$$E(x) = -\frac{d\varphi(x)}{dx}$$

Find the dose and type (donor or acceptor) of the channel implant so that the depletion depth X_d is exactly 0.1μm when $V_{GS} = V_{BS}$ = 0V (ε_o=8.85x10^{-14}F/cm, ε_{ox}=3.9ε_o, ε_{si}=11.7ε_o, ~~elementary~~ electron charge is-1.6x10^{-19}Cb)(15 *points*)

I write the equation that describes the potential function:

$$0.55V - \frac{-(\rho_0 X_d + Dq)}{\varepsilon_{ox}} T_{ox} - (-0.36V) = -\frac{\rho_0 X_d^2}{2\varepsilon_s} \Rightarrow$$

the only unknown is D!

$$0.55V + \frac{10^{-5}cm \cdot 1.6\cdot10^{-19}Cb \cdot 10^{16}/cm^3 + Dq}{3.9 \times 8.85\cdot10^{-14} F/cm} 10^{-6}cm + 0.36V = \frac{1.6\cdot10^{-19}\cdot10^{16}/cm^3\cdot(10^{-5}cm)^2}{2\cdot11.7\cdot8.85\cdot10^{-14}F/cm}$$

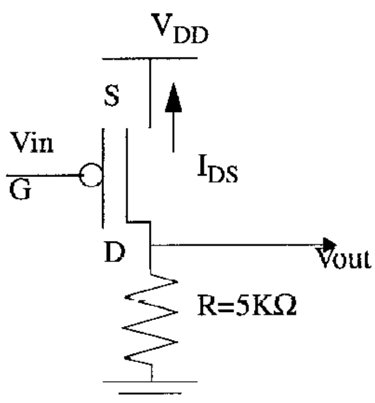
$$\Rightarrow 0.55V + 0.0464 + 0.36 - 0.0773 = -\frac{Dq}{3.45\cdot10^{-7}} \Rightarrow qD = -0.786\cdot3.45\cdot10^{-7} = -2.713\cdot10^{-7}\frac{Cb}{cm^2}$$

so, the implanted dose is $\frac{-2.713\cdot10^{-7}}{-1.6\cdot10^{-19}} cm^{-2} \Rightarrow D = 1.43\cdot10^{12}$ atom/cm² (acceptor)

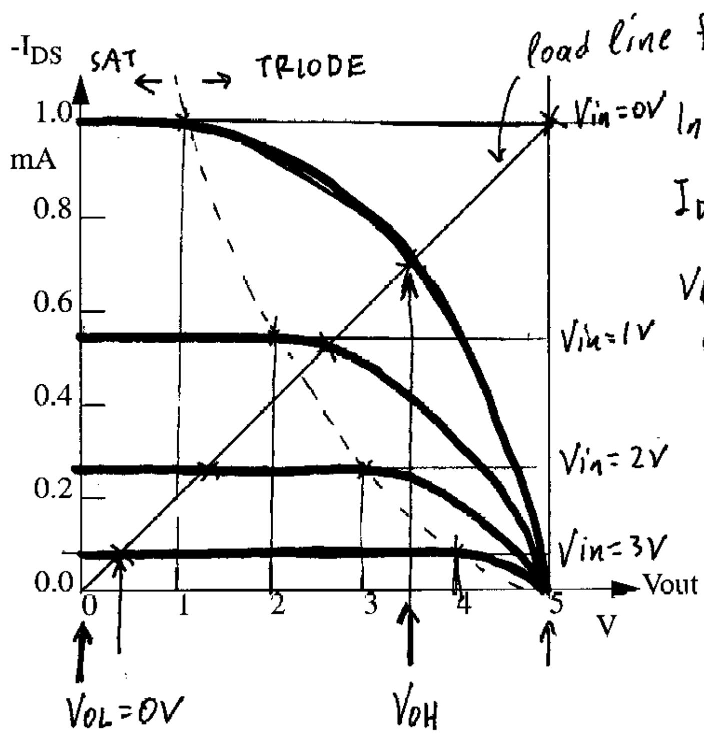
25

Problem 3 of 3 ([redacted] points)

You just found in your basement a batch of old, n-type wafers from the 70s. You decide to make some cheap inverters on them, just by using p-channel transistors and diffusion resistors. This is the design of the inverter you come up with:



Now, assume that W/L is 10/2, V_{DD} = 5V, Vtp=-1V, μ_pCox is 25μA/V^2 and λ_p=0V^{-1}. Sketch the load line diagrams for the resistor and the transistor, and mark the approximate values of Vout for Vin taking the values 0V, 1V, 2V, 3V 4V and 5V. [redacted].



In saturation

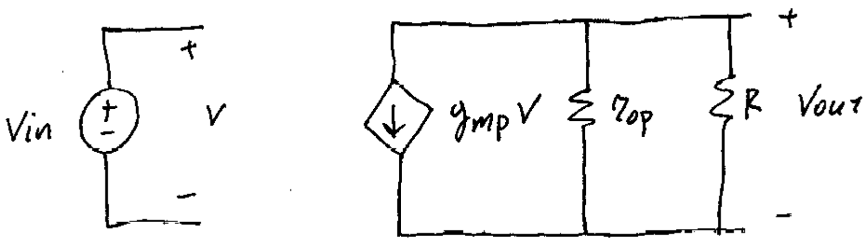
$K_p = \frac{W}{L}\mu_p C_{ox} = 125\,\mu A/V^2$

$I_{DS} = -\frac{1}{2}K_p\,(V_{SG} + V_{Tp})^2$

Vin	V_{SG}	I_{DS}	Vout
0	-5	-1mA	~3.5
1	-4	-0.5625mA	~2.5
2	-3	-0.25mA	~1.5
3	-2	-0.0625mA	~0.5
4	-1	0	0
5	0	0	0

(over)

Draw the small signal equivalent circuit and calculate Av when Vin = 2V. (*10 points*)



$r_{op} = \infty$ since $\lambda_p = 0\ V^{-1}$

$g_{mp} = K_p\left(V_{DD} - 2V + V_{Tp}\right) = 125\ \mu A/V^2 \cdot 2V = 250\ \mu A/V$

$A_v = \dfrac{V_{out}}{V_{in}} = -g_{mp} \cdot R = -250\ \mu A/V \cdot 5000 \cdot \dfrac{V}{A} = \underline{\underline{-1.25}}$ (not too great!)