# *Microelectronic Devices and Circuits- EECS105*

## *First Midterm Exam*

*Wednesday, October 6, 1999*

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*Department of Electrical Engineering and Computer Sciences*

*Your Name:* Official Solutions
*(last)* *(first)*

*Your Signature:* ____________________

1. *Print and sign your name on this page before you start.*
2. *<u>You are allowed a single, handwritten sheet with formulas. No books or notes</u>!*
3. *Do everything on this exam, and make your methods as clear as possible.*

| | |
|---|---|
| Problem 1 _______ | / 35 |
| Problem 2 _______ | / ~~40~~ 50 ← bonus points! |
| Problem 3 _______ | / 25 |
| TOTAL _______ | / ~~100~~ 110 |

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

What happens to $n_i$ if the temperature increases? Give a brief qualitative explanation (5pts)

increases, because of thermal generation of holes and electrons

What is the concentration of holes, electrons and positive/gnegative ions if Si is doped with $10^{17}$ Boron atoms/cm$^3$, and $10^{19}$ As atoms/cm$^3$ at room temperature? ($n_i = 10^{10}$)(5pts)

we have $10^{19} - 10^{17} \simeq 10^{19}$ electrons/cm$^3$

$n_i^2/10^{19} = 10$ holes/cm$^3$

$\sim 10^{17}$ negative Boron ions /cm$^3$

$\sim 10^{19}$ positive As ions /cm$^3$

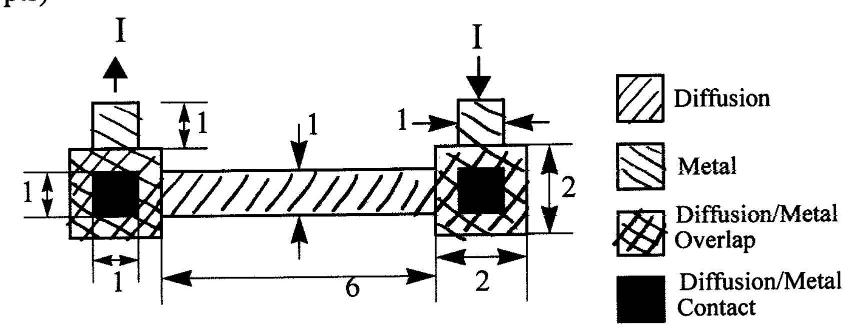
What are the three types of charges in an MOS capacitor under inversion? Mention carrier type (holes or electrons), ion polarity (positive or negative), charge nature (depletion, accumulation or inversion) and location (gate, substrate surface or bulk). (Gate is n+, bulk is p)/(6pts)

in gate: positive ions, (depletion)

in channel: free electrons (inversion)

in bulk: negative ions (depletion)

Find the resistance of the following structure (drawn to scale), if the $Rs_1$ (diffusion) is 20 Ω/square, $Rs_2$ (metal) is 1 Ω/square and contact hole conductivity (i.e. the area where the two layers touch) is 1Siemens/μm$^2$. (1Siemens = 1/Ω) Assume that "dogbone" contact areas amount to 0.65 squares. (6pts)




metal # of □s: $1 + 0.65 + 0.65 + 1 = 3.3$

diffusion # of □s: $6 + 0.65 + 0.65 = 7.3$

metal resistance $3.3 \times 1\,\Omega/\square = 3.3\,\Omega$

diffusion resistance $7.3 \times 20\,\Omega/\square = 146.\,\Omega$

contact resistance $2\,\Omega$

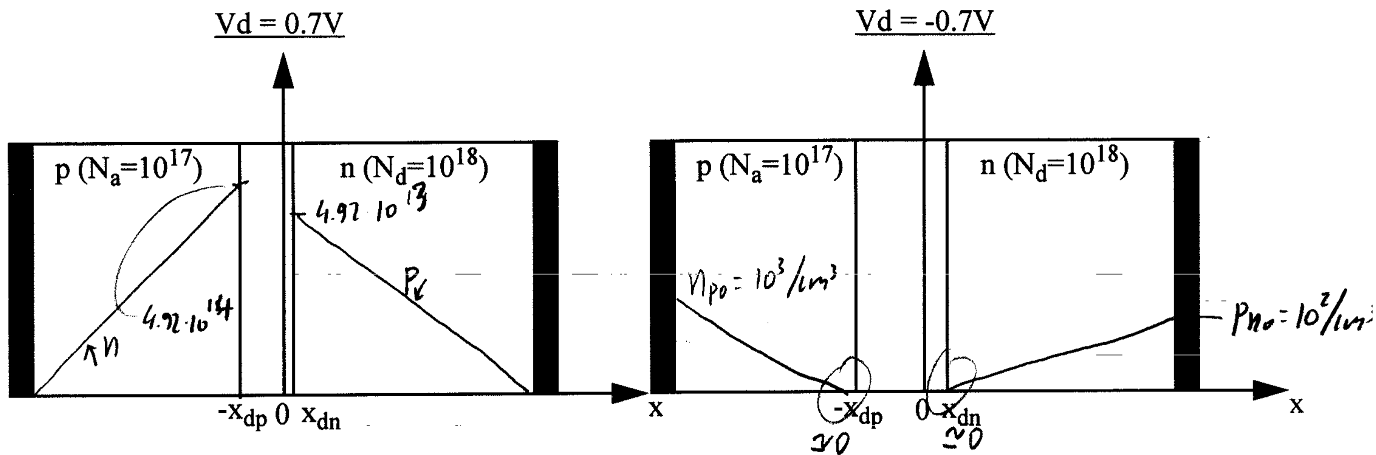
TOTAL $151.3\,\Omega$

What is the "law" of the junction? (5pts)

$p_n(x_n) = p_{no}\, e^{V_D/V_{th}} \qquad n_p(-x_p) = n_{po}\, e^{V_D/V_{th}}$

i.e. level of injected minority carriers depends exponentially on bias voltage.

Sketch the minority charge concentration in the bulk of a pn junction under forward bias, and also under reverse bias (no need to calculate the width of the depletion regions - assume that the diode is "short"). (8pts):



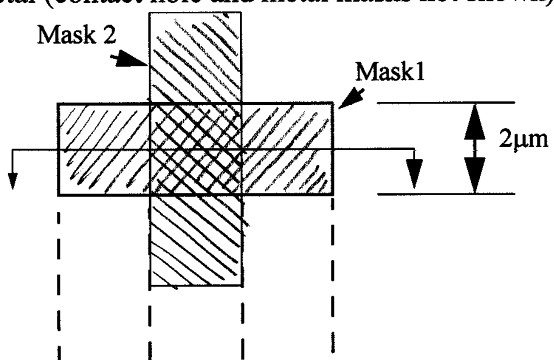

$n_{po} = 10^3/cm^3 \qquad p_{no} = 10^2/cm^3$

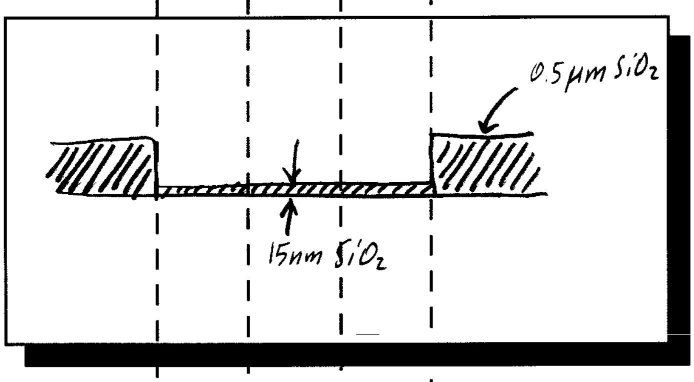
$e^{\frac{0.7}{0.026}} = 4.92\cdot 10^{14} \qquad e^{\frac{-0.7}{0.026}} \approx 0$

## Problem 2 of 3 (40 points)

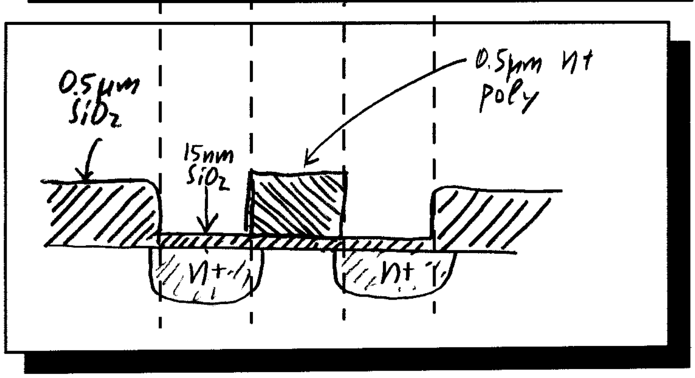
Follow these steps to create an MOS transistor:

0. Start with p-type $10^{17}/cm^3$ Boron susbstrate.
1. Grow 0.5μm of $SiO_2$ everywhere.
2. Use mask 1 to etch $SiO_2$ where mask 1 is dark.
3. Grow 15nm $SiO_2$ everywhere. (draw cross section after this step)
4. Deposit and pattern 0.5μm of n+ poly using mask 2 (poly remains where mask 2 is dark).
5. Implant n+ regions (to make source and drain) in areas *not* covered by poly or thick $SiO_2$. (draw cross section after this step).
6. Finish the device by cutting contact holes over source/drain, and by depositing oxide and patterning metal (contact hole and metal masks not shown) (*10 points*).



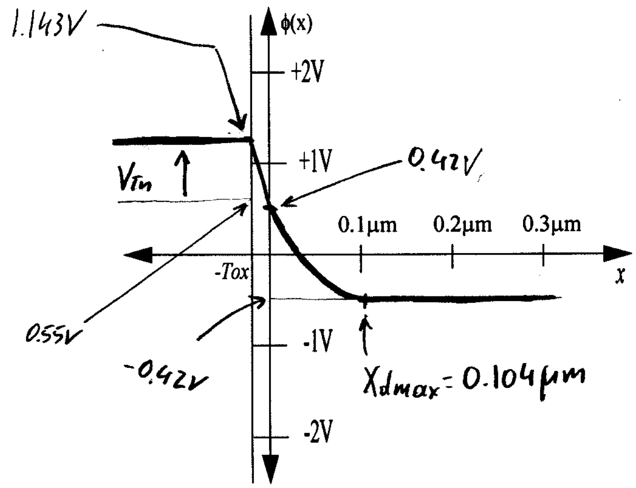




Cross section after step 3.




Cross section after step 5

After the transistor has been completed, apply $V_{DS}$=0V, $V_{BS}$=0V, and $V_{GS} = V_{tn0}$ to bring this device to the *onset of inversion*. Draw $\phi(x)$ (with reference to intrinsic silicon) and mark the values of $V_{tn0}$, $X_{dmax}$. ($\varepsilon_o$=8.85x10$^{-14}$F/cm, $\varepsilon_{ox}$=3.9$\varepsilon_o$, $\varepsilon_{si}$=11.7$\varepsilon_o$, electron charge is -1.6x10$^{-19}$Cb) (*10 points*).




(Tox not drawn to scale)

$$V_{Tn0} = V_{FB} - 2\varphi_p + \frac{1}{C_{ox}}\sqrt{2q\varepsilon_s N_a(-2\varphi_p)}$$

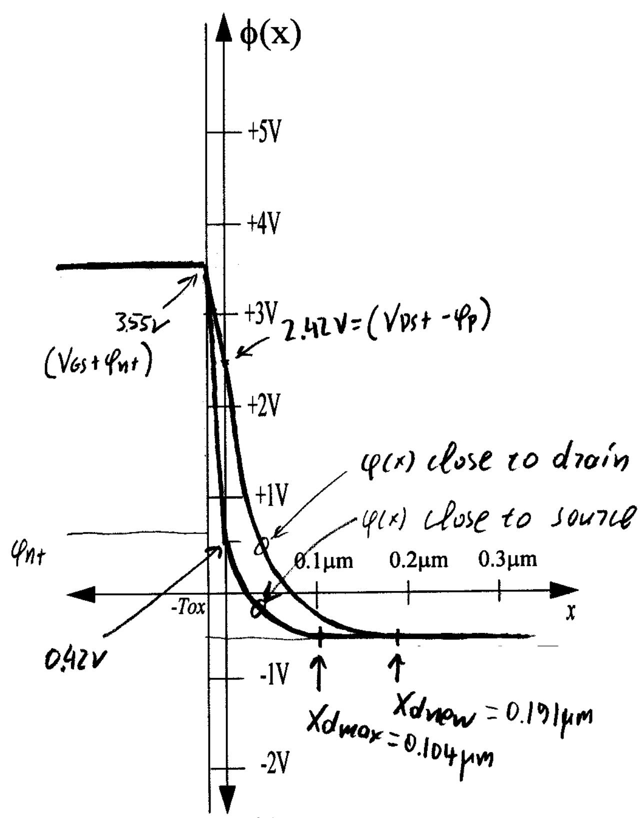
$V_{FB} = \varphi_{n+} - \varphi_p$ (0.55V, −0.42V); $C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$

$$\Rightarrow V_{Tn0} = -0.97 + 0.84 + \frac{166.4\cdot 10^{-9}\ Cb/cm^2}{230.0\cdot 10^{-9}\ F/cm^2} = 0.593V$$

$$X_{dmax} = \sqrt{2\frac{\varepsilon_s}{qN_a}(-2\varphi_p)} = 0.104\mu m$$

Apply $V_{BS}$ = 0V, $V_{DS}$ = 2V, $V_{GS}$=3V and draw $\phi(x)$ at a spot very close to the source, and also at a spot very close to the drain. Draw both plots on the same graph, but mark each plot carefully. (Hint: the bulk potential stays the same, at $\phi_p$ with reference to intrinsic silicon in both cases)(*15 points*).

Since $V_{DS} < V_{GS} - V_{Tn}$, the transistor is in triode.




(Tox not drawn to scale)

The plot of $\varphi(x)$ close to the source looks almost like the above plot, except for the gate and oxide potential.

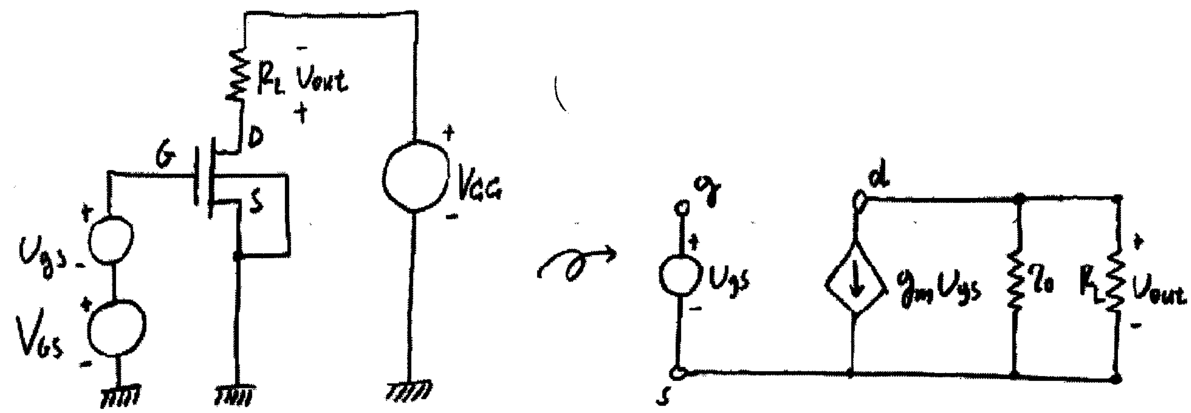
The plot of $\varphi(x)$ close to the drain has a higher channel potential, and as a result a deeper depletion. The gate potential and the bulk potential of these two plots is the same.

The new depletion depth is:

$$X_{dnew} = \sqrt{2\frac{\varepsilon_s}{qN_a}(-2\varphi_p + V_{DS})} = 0.191\mu m$$

Consider the small signal model for this transistor at $V_{GS}$=2V, $V_{BS}$=0V. The large signal source $V_{CC}$ is such that the transistor is saturated. Calculate the values of $g_m$ and $r_o$ (assume $\mu_n$=215cm$^2$V$^{-1}$s$^{-1}$, and that the channel-length modulation parameter $\lambda_n$ is 0.1V$^{-1}$). If we connect a small-signal source $v_{gs}$ = 1mV, what is the small signal voltage, $v_{out}$, across $R_L$ = 100KΩ connected as shown? (Do not take $\lambda_n$ into account when you calculate [redacted]). (*15 points*)

$g_m$




$$g_m = \frac{W}{L}\mu_n C_{ox}(V_{GS}-V_{Tn}) = 1 \cdot 215\,cm^2V^{-1}s^{-1}\,230\cdot 10^{-9}F\,cm^{-2}(2-0.593)V = 69.6\cdot 10^{-6}\text{ Siemens}$$

$$g_o = \frac{1}{r_o} = \left(\frac{W}{2L}\right)\mu_n C_{ox}(V_{GS}-V_{Tn})^2\lambda_n = 0.5\cdot 215\,cm^2 V^{-1}s^{-1}\,230\cdot 10^{-9}F/cm^2\cdot(2-0.593)^2\,0.1 = \frac{1}{204K\Omega}$$

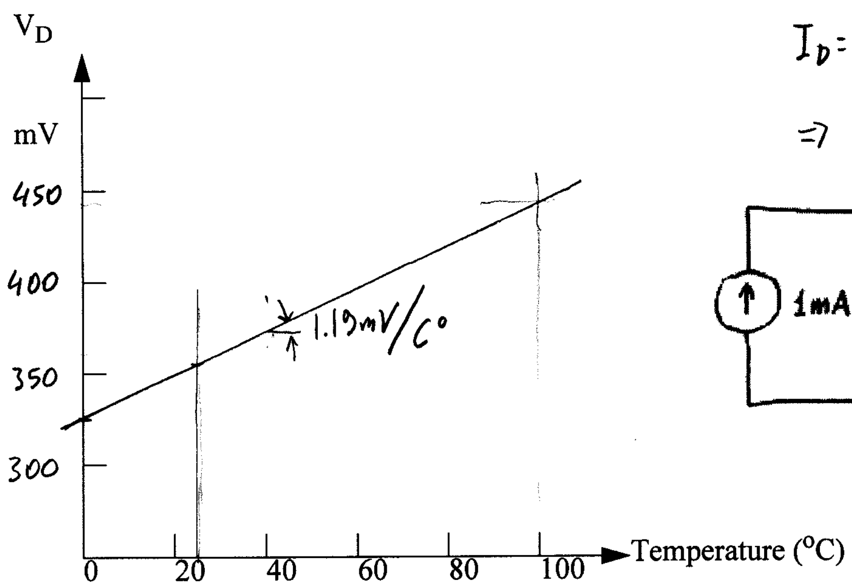
$$\Rightarrow r_o = 204K\Omega$$

$$v_{out} = -\underbrace{(R_L//r_o)}_{67.13K\Omega}g_m v_{gs} = -67.13\,10^3\cdot 69.6\,10^{-6}\cdot 10^{-3}V = -4.67\cdot 10^{-3}V$$

i.e. there is almost a -5x amplification!

## Problem 3 of 3 (25 points)

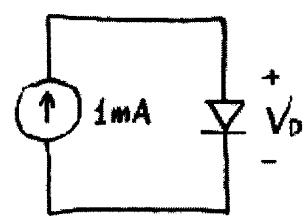
Consider a short pn junction with $I_o = 10^{-9}$A. You want to make a thermometer out of this diode, by feeding it with a constant forward current of $10^{-3}$A, and by reading the bias voltage. What kind of function of temperature will be this voltage? (linear or some other kind?) Calculate the $V_D$ values for 0°C, 25°C and 100°C. Graph the relationship between temperature and $V_D$. (Boltzman's constant is 1.38 $10^{-23}$ J/K. The absolute zero temperature is at 0°K or at -273°C.) (*15 points*)




$I_D = I_o e^{\frac{V_D}{V_{th}}}$  $V_{th} = \frac{KT}{q}$

$\Rightarrow \ln \frac{I_D}{I_o} = \frac{V_D \cdot q}{KT} \Rightarrow V_D = \frac{KT}{q} \ln \frac{I_D}{I_o}$

13.81




it is clear that $V_D$ is a linear function of temp.

| T | K | $V_D$ (mV) |
|---|---|---|
| 0°C | 273° | 325 |
| 25°C | 298° | 354 |
| 100°C | 373° | 444 |

How would a npn BJT be affected by the following parameters (draw up or down arrows to indicate that a parameter increases or decreases, respectively, given an increase of the respective design variable.) (*10 points*)

| Design Variable | $\beta_F$ | $\alpha_F$ |
|---|---|---|
| Emitter Doping | ↑ | ↑ |
| Emitter Width | ↑ | ↑ |
| Base Doping | ↓ | ↓ |
| Base Width | ↓ | ↓ |

emitter doping lowers hole injection into emitter
emitter width lowers hole diffusion current
base doping lowers electron injection into base
base width lowers electron diffusion current

$\beta_F = \frac{\alpha_F}{1-\alpha_F}$ i.e. when $\beta_F$ improves, so does $\alpha_F$