Santa Clara University

Department of Electrical and Computer Engineering

No. ______ DAREN LIU Submitted on: 10/22/20

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ELEN 153 **Problem Set #4** **Due: 10-22-2020, Thursday, 12:00 pm**
Fall 2020

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1. Consider the logic function $g = \overline{(a+b) \bullet (c+d) \bullet e}$. a) Draw the logic diagram and the transistor circuit.
25 b) Construct a layout for the circuit using stick diagram with single level interconnect lines.

2. A silicon specimen is doped with 3.54 x10^{10}/cm^3 Boron acceptors and 4.62 x10^{10}/cm^3 Phosphorus donors.
20 a) Calculate free electron and hole #/cm^3 concentrations. b) Determine polarity type (n or p) of the specimen.

3. A silicon specimen is doped with 6x10^{16}/cm^3 Aluminum.
25
   a) Find the free majority and minority charge carrier (electron, hole) #/cm^3 concentrations.
   b) Calculate these free electron and hole mobility from i) Equation 3.33 (see below) and ii) the Mobility chart.
   c) Calculate and compare Ωcm resistivities of the specimen using mobility values from i) and ii) in b).

4. A Si block doped with 4x10^{15}/cm^3 Indium is compensated by doping with additional 2.6 x10^{16}/cm^3 Antimony.
25
   a) Find free majority and minority charge carrier #/cm^3 concentrations and b) Ωcm resistivity of the block.
   c) The block has dimensions of 1.73 μm x 0.58 μm x 4.27 μm. A voltage is applied to the block across three possible end-to-end faces. Sketch the three configurations and calculate resistance of the block in each case. Use electron and hole mobility from the Mobility chart.

5. A Si CMOS process uses an n-Si substrate with donor concentration of 5x10^{15}/cm^3. A p-well is fabricated by introducing additional 7x10^{15}/cm^3 acceptors into a section of the n-Si substrate. Heavily doped (10^{19}/cm^3) p$^+$and n$^+$ Source and Drain regions are then fabricated just below the surface of the n-Si substrate and the p-well, respectively. A 45 nm thick gate oxide layer is grown above and between the source drain regions in the n-Si substrate and the p-well. Finally, a metal layer is deposited on top of these two oxide layers. Sketch and label a cross-section of the CMOS device showing the n-FET and the p-FET structures.
25
   a) Calculate per unit area oxide capacitance of the nFET and the pFET in fF/μm^2.
   b) Use the Mobility chart and find μA/V^2 Process transconductances of the nFET and the pFET.

Equation 3.33 (page 82) : $\mu = \mu_1 + [(\mu_2 - \mu_1) / \{1 + (N/N_{ref})^{\alpha}\}]$

For Si (300K):	*Electron*	*Hole*
μ_1 (cm^2/v.s)	92	47.7
μ_2 (cm^2/v.s)	1380	495
N_{ref} (#/cm^3)	1.3 x 10^{17}	6.3 x 10^{16}
α	0.91	0.76

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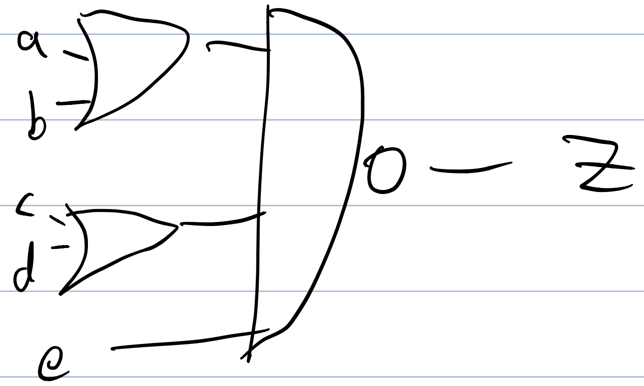
1) a)

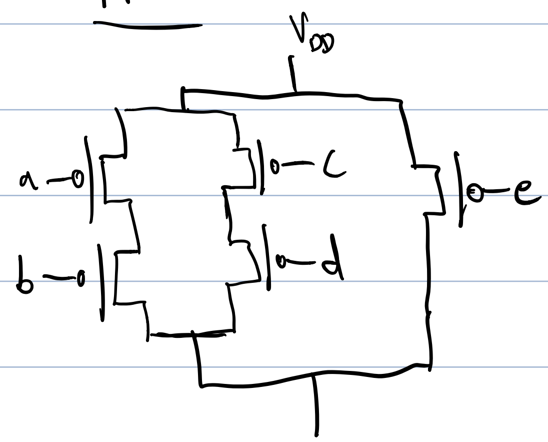
Liu ①

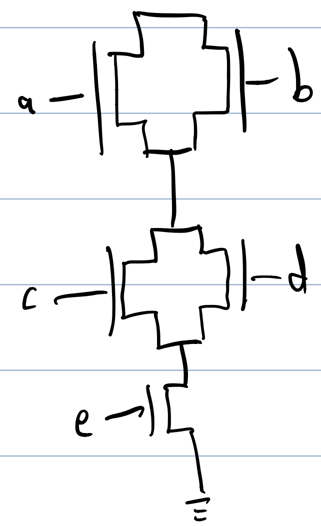


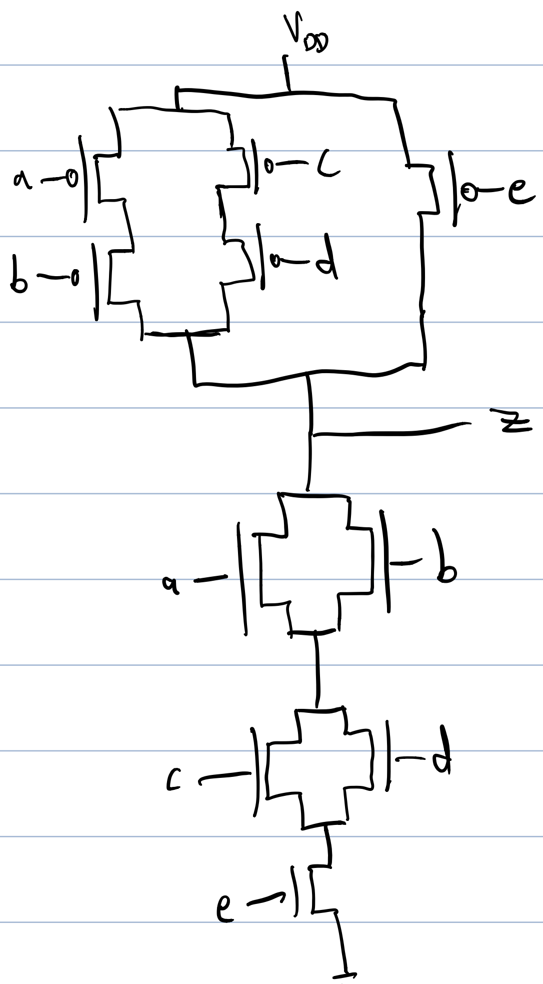
$$\overline{(a+b)\cdot(c+d)\cdot e} = (\overline{a}\cdot\overline{b}) + (\overline{c}\cdot\overline{d}) + \overline{e}$$

pFET

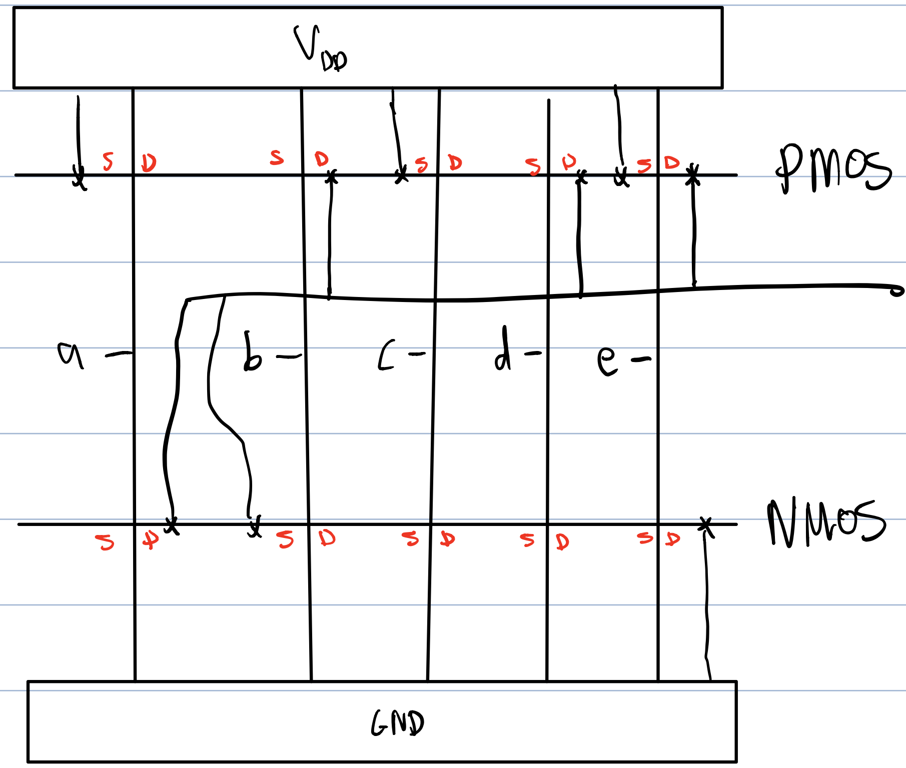
nFET







b)



2) Boron 3 valence electrons $3 < 4$, acceptor

$N_A^- = 3.54 \cdot 10^{10} / cm^3$

Phosphorus 5 valence electrons $5 > 4$, donor

$N_D^+ = 4.62 \cdot 10^{10} / cm^3$

$N_A^- < N_D^+$: n-type $\qquad n_i = 1.45 \cdot 10^{10}$

$$n = \frac{1}{2}(N_D^+ - N_A^-) + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$= \frac{1}{2}(4.62 \cdot 10^{10} - 3.54 \cdot 10^{10}) + \sqrt{\left(\frac{4.62 \cdot 10^{10} - 3.54 \cdot 10^{10}}{2}\right)^2 + (1.45 \cdot 10^{10})^2}$$

$= 2.09 \cdot 10^{10}$ #$/cm^3$

$p = \frac{(n_i)^2}{n} = \frac{(1.45 \cdot 10^{10})^2}{(2.09 \cdot 10^{10})} = 1.01 \cdot 10^{10}$ #$/cm^3$

b) n-type

3) a) Aluminum valence electrons $3 < 4$, acceptor

$N_A^- = 6 \cdot 10^{16} \qquad N_D = 0$

$N_A^- > N_D \qquad$ p-type

$p = 6 \cdot 10^{16}\ \#/cm^3$ majority

$n = \frac{(1.45 \cdot 10^{10})^2}{6 \cdot 10^{16}} = 3504.17\ \#/cm^3$ minority

b) i) $N = p = 6 \cdot 10^{16}$

Electron

$\mu_n = 92 + \frac{1380 - 92}{1 + (6 \cdot 10^{16} / 1.3 \cdot 10^{17})^{0.91}} = 953.65\ cm^2/V.s$

Hole

$\mu_p = 47.7 + \frac{495 - 47.7}{1 + (6.10^{16} / 6.3 \cdot 10^{16})^{0.76}} = 275.50\ cm^2/V.s$

ii) $\mu_n \simeq 986 \qquad \mu_p \approx 378$

c) $\rho = \frac{1}{|q|(\mu_n n) + |q| \mu_p p}$

$= \frac{1}{(1.602 \cdot 10^{-19})(953.65 \cdot 3504.17 + 275.5 \cdot 6 \cdot 10^{16})} = 0.378\ \Omega\text{-cm}$

$\rho = \frac{1}{(1.602 \cdot 10^{-19})(986 \cdot 3504.17 + 378 \cdot 6 \cdot 10^{16})} = 0.275\ \Omega\text{-cm}$

4) a) Indium valence electron: 3 $\quad 3 < 4$, acceptor $N_A = 4 \cdot 10^{15}$

Antimony valence electron: 5 $\quad 5 > 4$ donor $N_D = 2.6 \cdot 10^{16}$

$N_D > N_A$: n-type

$n = (2.6 \cdot 10^{16} - 4.10^{15})/2 + \sqrt{\left(\frac{2.6 \cdot 10^{16} - 4 \cdot 10^{15}}{2}\right)^2 - (1.45 \cdot 10^{10})^2}$

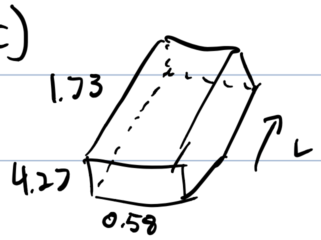
$= 2.2 \cdot 10^{16}\ \#/cm^3$

$p = \frac{n_i^2}{n} = \frac{(1.45 \cdot 10^{10})^2}{2.2 \cdot 10^{16}} = 9556.82\ \#/cm^3$

b) $\mu_n \approx 1165 \quad \mu_p \simeq 419$

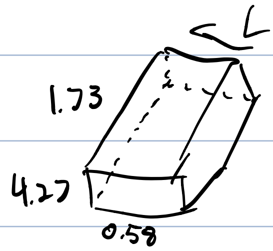
$\rho = \frac{1}{(1.602 \cdot 10^{-19})(1165 \cdot 2 \cdot 10^{16} + 419 \cdot 9556.82)} = 0.268\ \Omega\text{-cm}$

c)

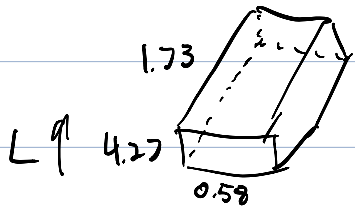


$R = \rho\left(\frac{L}{A}\right) = (0.268)\left(\frac{1.73}{4.27 \cdot 0.58}\right)\left(\frac{10^4\ \mu m}{1\ cm}\right)$

$= 1872.08\ \Omega$

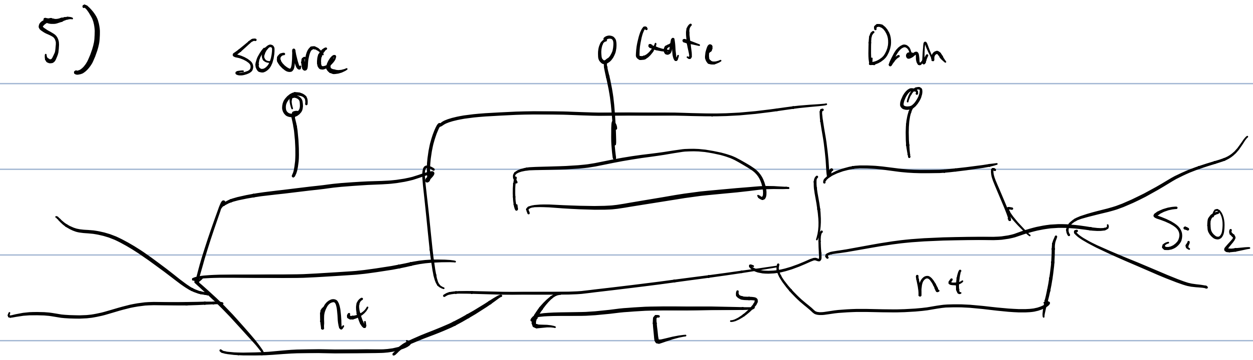


$$R = \rho\left(\frac{L}{A}\right) = (0.268)\left(\frac{0.58}{1.73 \cdot 4.27}\right)(10^4)$$
$$= 210.42\ \Omega$$



$$R = \rho\left(\frac{L}{A}\right) = (0.268)\left(\frac{4.27}{1.73 \cdot 0.58}\right)(10^4)$$
$$= 11404.82\ \Omega$$

5)



a) $$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.9(8.854 \cdot 10^{-14}) \cdot 10^{-6}\,\mu m}{45 \cdot 10^{-9}\,m \cdot (10^6)} = 7.67 \cdot 10^{-18}\ F/\mu m^2$$

b) $N_A = 7 \cdot 10^{15}$ $\quad N_D = 5 \cdot 10^{15}$

$$N = N_A + N_D = 1.2 \cdot 10^{16}$$

$\mu_n \approx 1248$ $\quad \mu_p \approx 437$

$$K'_n = (1248)\left(7.67 \cdot 10^{-18}\ \frac{F}{\mu m^2}\right)(1000)^2 = 9.57 \cdot 10^{-9}\ \mu A/V^2$$

$$K_p' = (437)(7.67 \cdot 10^{-18})(1000)^2 = 3.35 \cdot 10^{-9}\ \mu A/V^2$$