Q1 Band diagrams of a MOS capacitor for three different values of the gate voltage V_G are shown in figure 1. V_t is its threshold voltage. All the variables shown in figure 1 have their usual meanings. [40 pts]

[Q1.1] Based on the information provided in figure 1, find out whether V_G larger or smaller than V_t for each of the three cases. Briefly explain your answer. [15 pts]

[Q1.2] Find out the values of electron density and hole density at x=0 and x=60 nm for each of the three cases. Assume that N_C=N_V=10^{25} /m^3, kT=25 meV, E_G= 1.1 eV (all variables have their usual meaning). [25 pts]

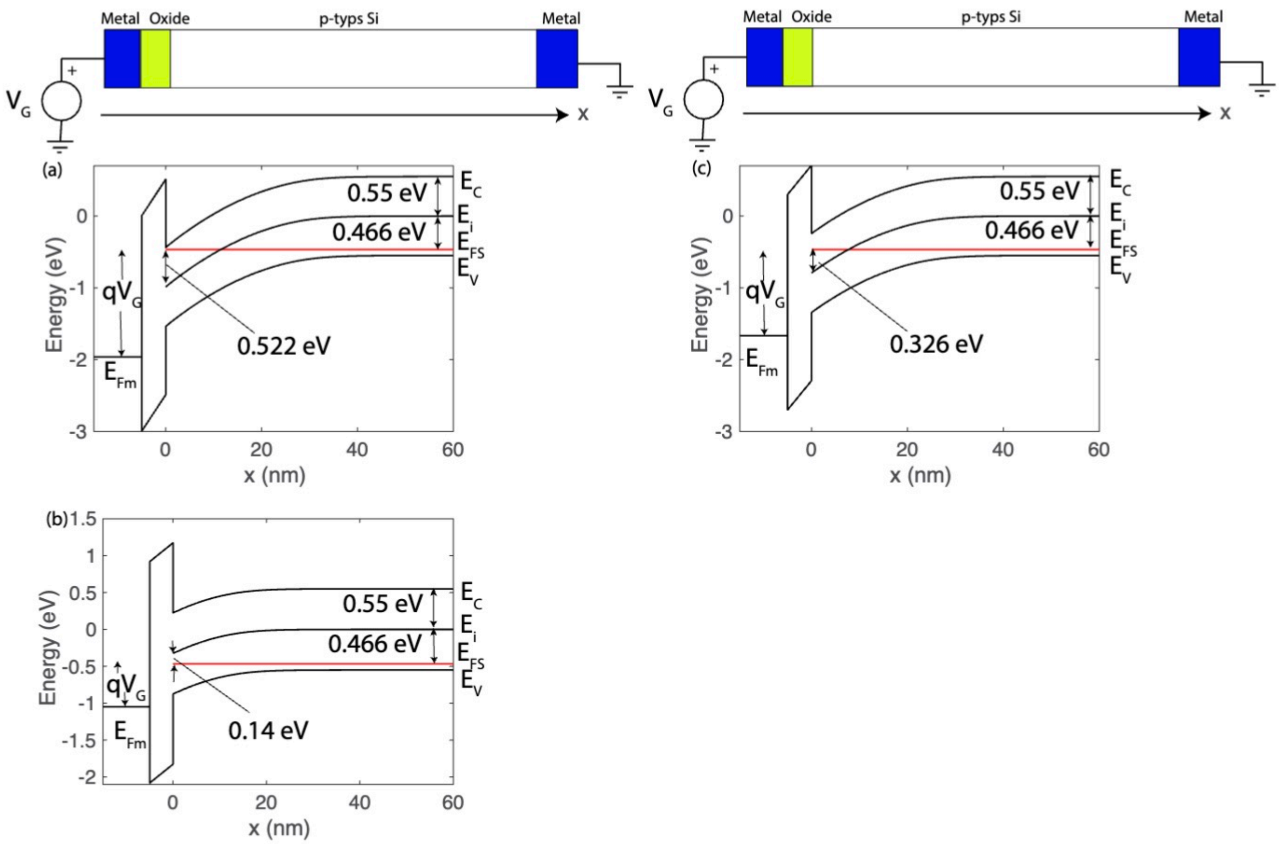


Figure 1: Band diagrams of a MOS capacitor at different gate voltages.

Q 1.1) The Difference in Valence Band and Fermi level
a) is .466 eV. Given that intrinsic E and Fermi E
have .522 eV Diff => > valence Diff => $V_g > V_t$

b) Since $E_{Fs} - E_i$ = .14 eV < .466 => $V_g < V_t$

c) .326 eV ($E_{Fs} - E_i$) is < .446 => $V_g < V_t$

Q 1.2) a) $N_c = N_v = 10^{25}$

$kT = 25meV$

$E_g = 1.1 eV$

$n = N_c e^{-(E_c + E_{fs})/kT}$

$P = N_v e^{-\frac{(E_v + E_{fs})}{kT}}$

@ $x = 0$ for Graph A

$E_c = .55 - E_{fs} = .028 eV$

$\Rightarrow n = (10e^{25})(e^{-(.028/.025)}) = \boxed{3.26 E 24 \; m^{-3}}$

$P = (10e^{25})(e^{-1.072/.025}) = \boxed{2.38 E 6 \; m^{-3}}$

$x = 60$ $n = (10E25)(e^{-(.55+.460)/.025}) = \boxed{2.24 E 7 \; m^{-3}}$

$P = (10E25)(e^{-(.55-.460)/.025}) = \boxed{3.47 E 23 \; m^{-3}}$

b) $x = 0$

$n = (10E25)(e^{-(.55+.14)/.025}) = \boxed{1.03 E 13 \; m^{-3}}$

$P = (10E25)(e^{(.55-.14)/.025}) = \boxed{7.54 E 17 \; m^{-3}}$

@ x = 60, Density is the same since the transistor is switched off and no current is in the inversion region

c) $x = 0$

$n = N_c(e^{-(.55-.326)/.025}) = \boxed{1.23 E 21 \; m^{-3}}$

$P = N_v(e^{-(.55+.326)/.025}) = \boxed{6.05 E 9 \; m^{-3}}$

Since $V_g < V_T$, no inversion created $\Rightarrow$ x@ 60 nm is still same density.

Q2 In class, we have derived an expression for the threshold voltage V_t in an n-type MOSFET. How does V_t change if the following parameters are increased. [30 pts]

Q2.1 Acceptor doping density, N_a.

Q2.2 Oxide thickness, t_{ox}.

Q2.1 Dielectric constant of oxide, ϵ_{ox}.

Q2.1) Given that $V_t = 2q\psi_B + \dfrac{\sqrt{4\varepsilon_0 \varepsilon_{si} q^2 N_a \psi_B}}{C_{ox}}$

$V_t \propto N_a \Rightarrow$ increasing N_a will increase V_t

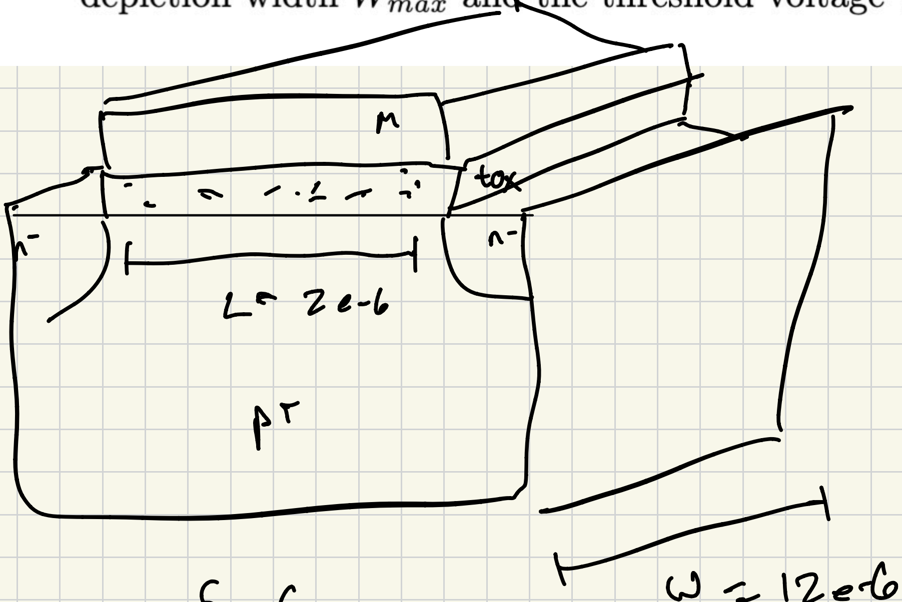
Q2.2) $C_{ox} = \dfrac{\varepsilon_0 \varepsilon_{ox}}{t_{ox}} \Rightarrow$ as $t_{ox} \uparrow$, $C_{ox} \downarrow$

as $C_{ox} \downarrow$, $V_t \uparrow$

Q2.3) By Q2.2, as $\varepsilon_{ox} \uparrow$, $C_{ox} \uparrow \Rightarrow V_t \downarrow$

Q3 Consider an n-type MOSFET with N_A=7×10^{18} m^3. The gate length of the MOSFET L=2 μm, width W=12 μm and the oxide thickness t_{ox}= 8 nm. Take N_C=N_V=10^{25} m^{-3}, E_G=1.12 eV, n_i=1.5×10^{16} m^{-3}, kT=0.026 eV, vacuum permittivity $\varepsilon_\circ$=8.854×10^{-12} F/m, dielectric constant of oxide ε_{ox}=4, dielectric constant of silicon ε_{Si}=12, electron mobility μ_n=230×10^{-4} m^2/Vs, hole mobility μ_p=83 ×10^{-4} m^2/Vs.

Calculate $\phi_B = |E_F - E_i|/q$, the oxide capacitance C_{ox}, the maximum depletion width W_{max} and the threshold voltage V_t. [30 pts]



$t_{ox} = 8e-9$

$$C_{ox} = \frac{\varepsilon_0 \varepsilon_{ox}}{t_{ox}} = \frac{(8.854e-12)(4)}{(8e-9)} = \boxed{4.43E-3 \ F/m^2}$$

$$\psi_B = \frac{E_i - E_f}{q} = \frac{.55 - .368}{q} = \boxed{\frac{.182 \ eV}{q}}$$

W max depletion width is Defined as

$$\frac{\sqrt{2 \varepsilon_0 \varepsilon_{Si} (2\psi_B)}}{\sqrt{q N_a}} = \frac{2\sqrt{(8.854E-12)(.182)(12)}}{\sqrt{q^2 (7E18)}} = \boxed{8.54E-6 \ m}$$

$$V_t = 2\psi_B + \frac{\sqrt{4 \varepsilon_0 \varepsilon_{Si} N_a \psi_B}}{C_{ox}} = (.182)(2) + \frac{2\sqrt{(8.854e-12)(12)(7E18)(.182)(q)}}{(4.43e-3)}$$

$$\Rightarrow \boxed{.886 \ eV}$$