ECE4904 Lecture 12 (12/6/18)

MOS Capacitor Review (16.1)
- Energy Band Diagram (16.2.1)
  - Flat Band potential ϕ_F
  - Surface potential ϕ_S
- Accumulation/Depletion/Inversion (16.2.2)
  - "Delta-Depletion" solution
- Threshold Voltage (16.3)

MOSFET Quantitative (17.2)
- Surface Mobility
- "On" Resistance (Triode region)
- Square Law (Saturation region)

Handout package:
- MOS Capacitor One Minute Quiz
- MC14007 NMOS/PMOS data sheet
- MOSFET Operating Regions
- Channel Length Modulation
- MOS V-I One Minute Quiz

HW 5 due 4pm in ECE office tomorrow Friday 12/7

Critical Quantities:

FAR FROM SURFACE

MOS structure:

ϕ_F Flat Band potential $\frac{1}{q}(E_i - E_F)$

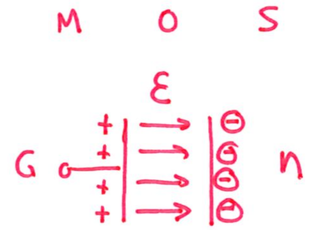
x_O Oxide thickness

Change with applied voltage:

ϕ_S Surface potential

ECE4904 MOS Capacitor "One Minute Quiz"

For each MOS capacitor situation described,



ACCUMULATION

i) Determine the value of the flat band potential ϕ_F
ii) sketch the energy band diagram
iii) sketch the block charge diagram
iv) determine if operating region is accumulation, depletion, or inversion

DOPED n-TYPE

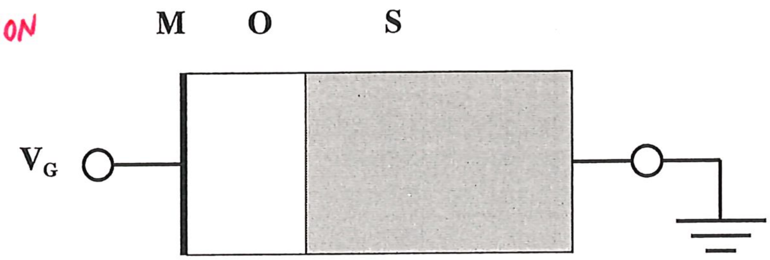
a) Semiconductor doping $N_D = 4.0E+16$ donor/cm^3 ; $V_G > 0$

i) $\phi_F =$ $\underline{-0.394V}$

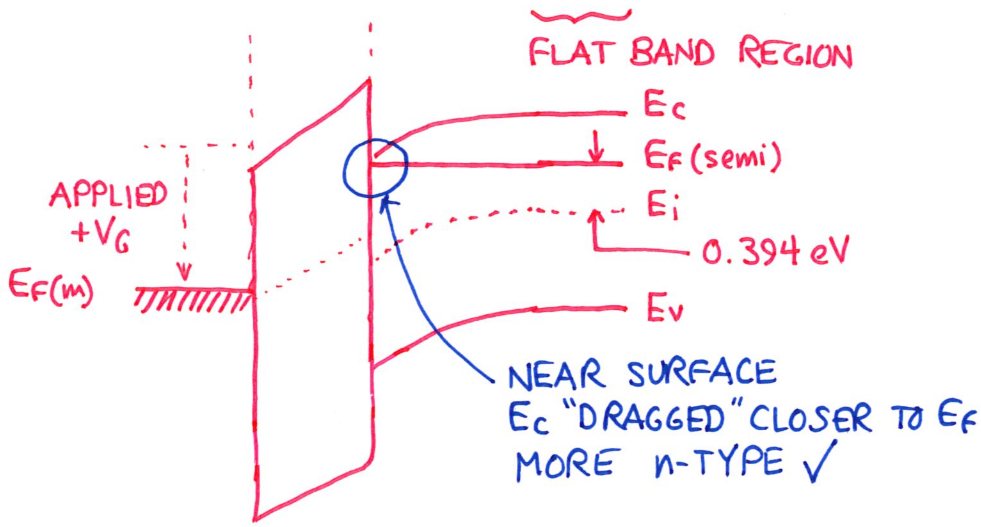
$E_i - E_F$ IN BULK REGION FAR FROM SURFACE

$$\phi_F = \frac{-kT}{q} \ln\left(\frac{N_D}{n_i}\right)$$

$$-0.0259 \ln\left(\frac{4E+16}{1E+10}\right)$$

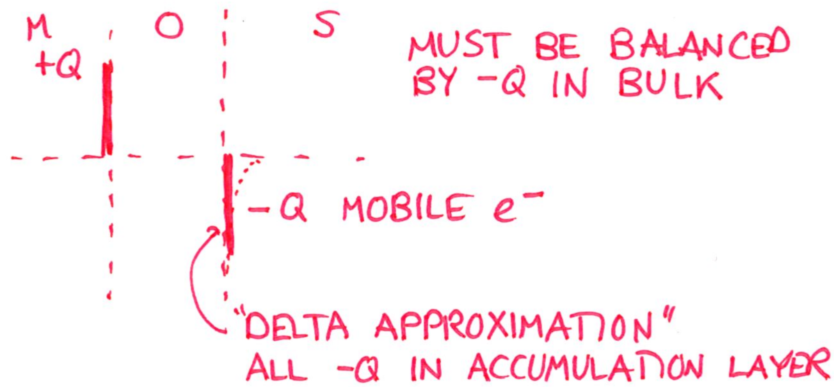


ii) Energy band diagram :



iii) Block charge diagram :

POSITIVE V_G



iv) Operating region (circle one):

ACCUMULATION DEPLETION INVERSION

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ECE4904 MOS Capacitor "One Minute Quiz"

For each MOS capacitor situation described,

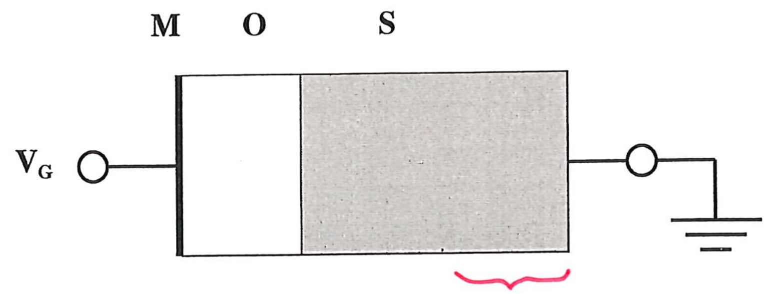
i) Determine the value of the flat band potential ϕ_F
ii) sketch the energy band diagram
iii) sketch the block charge diagram
iv) determine if operating region is accumulation, depletion, or inversion

DOPED p-TYPE

b) Semiconductor doping $N_A = 1.0E+17$ acceptor/cm^3 ; $0 < V_G < V_T$

i) $\phi_F =$ <u>+0.418</u>

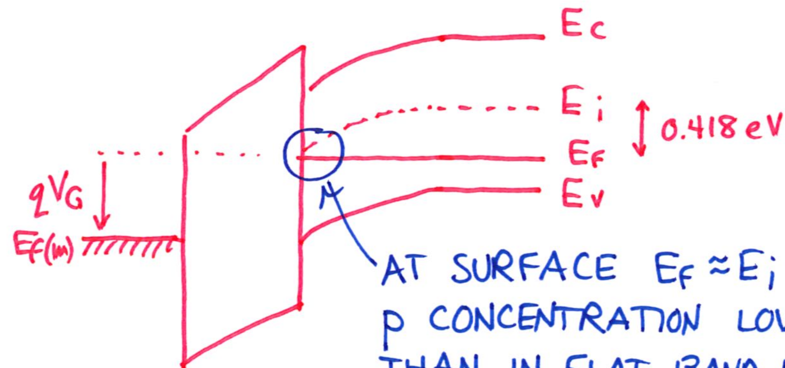
$.0259 \ln\left(\frac{1E+17}{1E+10}\right)$



FLAT BAND

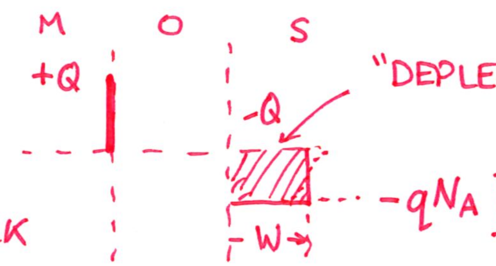
ii) Energy band diagram :

POSITIVE V_G



AT SURFACE $E_F \approx E_i$
p CONCENTRATION LOWER THAN IN FLAT BAND REGION

iii) Block charge diagram :



"DEPLETION APPROXIMATION"

DEPLETION OF BULK NEAR SURFACE

AS V_G INCREASES:
+Q INCREASES
TO BALANCE -Q IN BULK
W MUST INCREASE
(UNTIL $V_G = V_T$)

iv) Operating region (circle one):

ACCUMULATION DEPLETION INVERSION

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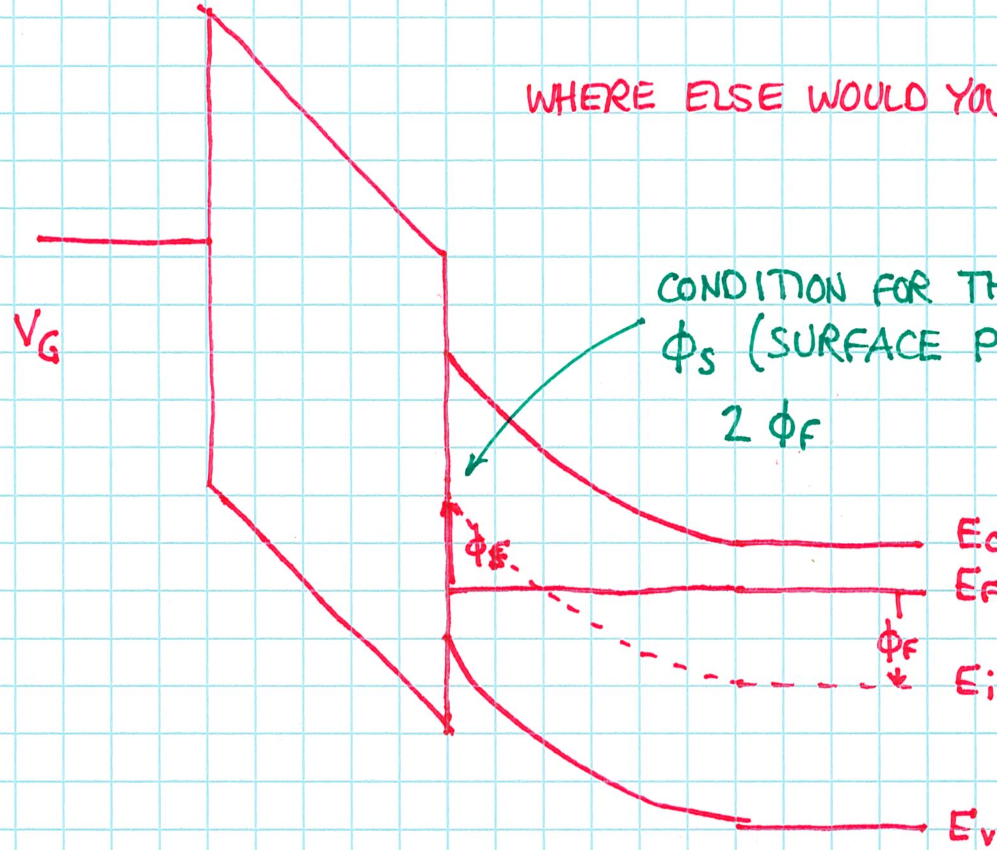
WHERE ELSE WOULD YOU SEE E_F?



CONDITION FOR THRESHOLD VOLTAGE

ϕ_S (SURFACE POTENTIAL)

$2\phi_F$

2 PARTS TO V_{TH}

VOLTAGE DROP IN OXIDE (INTEGRATE CONSTANT $\mathcal{E}$ FIELD)

INVERT SURFACE $2\phi_F$

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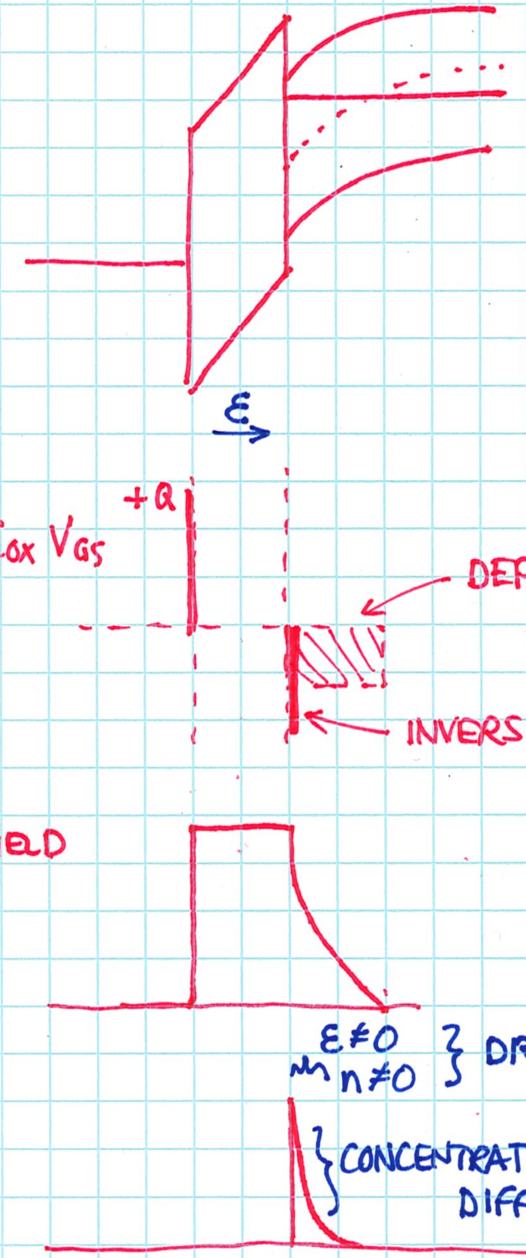
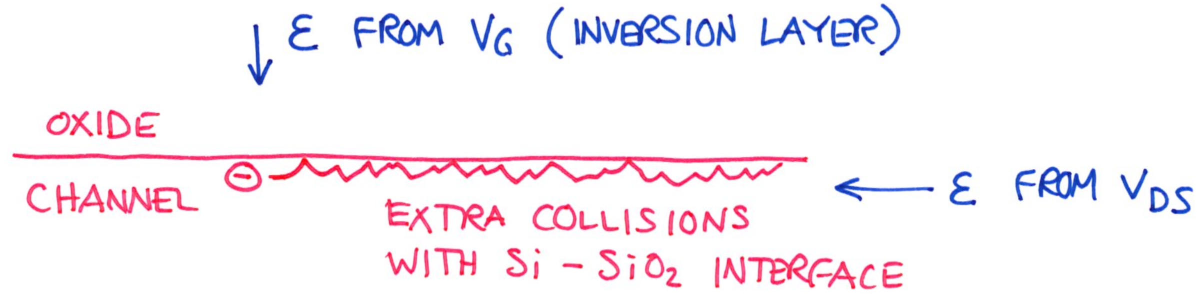
$V_G > V_T$


$\mathcal{E}$
+Q
$C_{ox} V_{GS}$
DEPLETED BULK $C_{ox}(V_T)$
INVERSION LAYER $C_{ox}(V_{GS} - V_T)$
$\mathcal{E}$ FIELD
EQUILIBRIUM:
ZERO NET CURRENT
$\mathcal{E} \neq 0$, $n \neq 0$ } DRIFT CURRENT!
n
MOBILE e^-
} CONCENTRATION GRADIENT
DIFFUSION WILL BALANCE

"SURFACE MOBILITY" $\bar{\mu}$



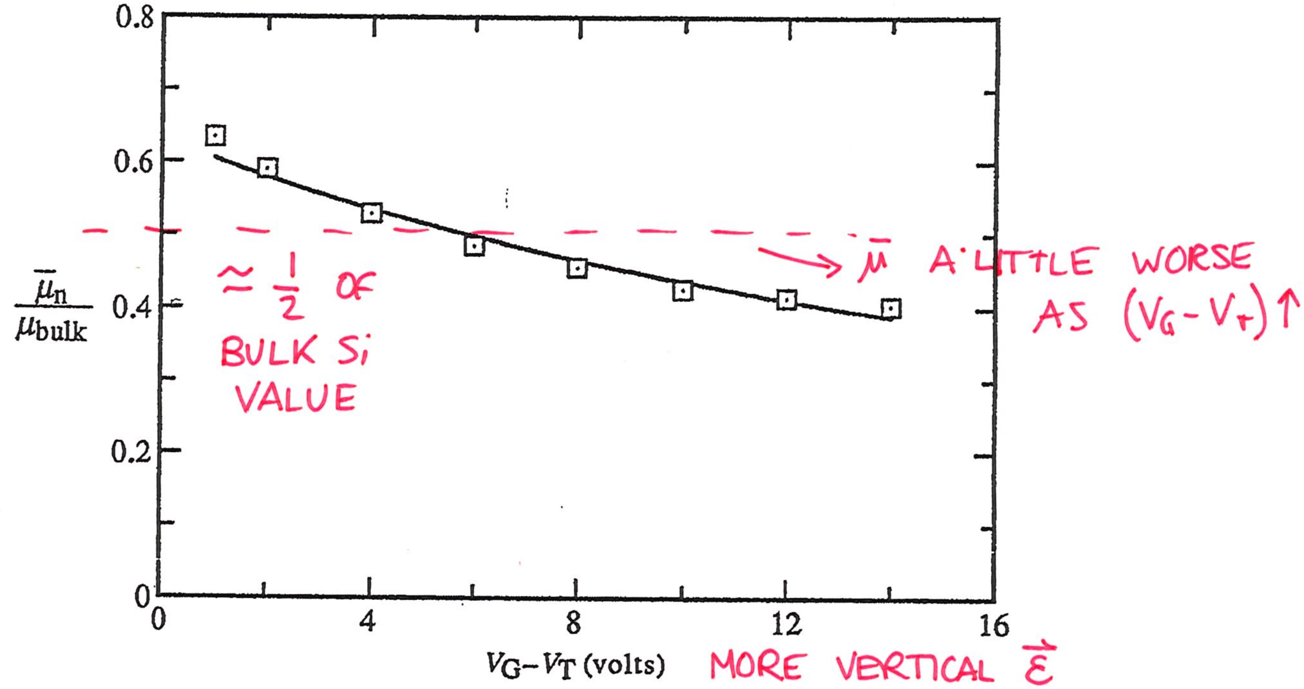
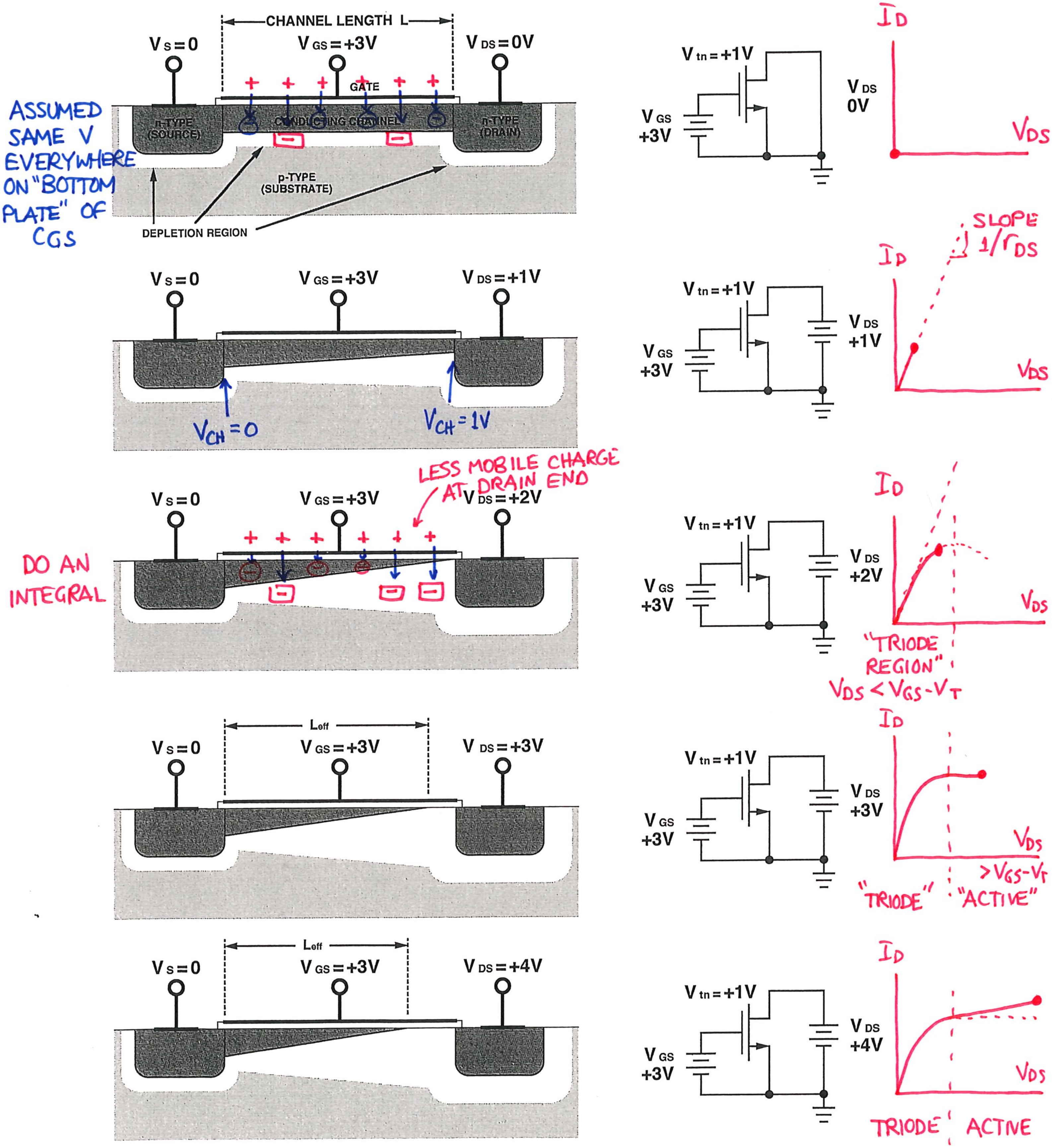


Figure 17.7 Sample variation of $\bar{\mu}_n$ with the applied gate voltage ($V_D \cong 0$). Data (⊡) from Sun and Plummer[16]. Equation (17.5) was used to construct the solid-line curve. (μ_{bulk} = 1340 cm^2/V-sec, μ_0 = 847 cm^2/V-sec, and θ = 0.0446/V.)

EE4902 MOSFET CHANNEL LENGTH MODULATION



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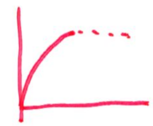
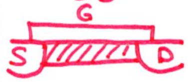
N-CHANNEL MOSFET OPERATING REGIONS

GATE	DRAIN	REGION	FIRST ORDER BEHAVIOR	NOT EXACTLY:
	$V_{DS} > V_{GS} - V_T$ LARGE V_{DS} 	ACTIVE SATURATION	DRAIN "LOOKS LIKE" CURRENT SOURCE; I_D DEPENDS ONLY ON (V_{GS} - V_T.) $I_D = \frac{\overline{\mu}_n C_O}{2}\frac{Z}{L}(V_{GS} - V_T)^2$ INDEPENDENT OF V_{DS}	CHANNEL LENGTH MODULATION 
$V_{GS} > V_T$ INVERSION	$V_{DS} < V_{GS} - V_T$ SMALL V_{DS} 	TRIODE	DRAIN-SOURCE CHANNEL "LOOKS" RESISTIVE $r_{DS} = V_{DS} / I_D$  R CONTROLLED BY V_{GS} - V_T. $r_{DS} = \frac{1}{\overline{\mu}_n C_O \frac{Z}{L}(V_{GS} - V_T)}$	NONLINEAR AS V_{DS} INCREASES  FULL TRIODE REGION EQUATION: $\int$ INTEGRAL $I_D = \overline{\mu}_n C_O \frac{Z}{L}\left[(V_{GS} - V_T)V_{DS} - \underbrace{\frac{V_{DS}^2}{2}}_{}\right]$ GOES TO ZERO IF V_{DS} SMALL
$V_{GS} < V_T$ DEPLETION ACCUMULATION		CUTOFF	$I_D = 0$ OFF	$I_D \approx 1$ pA LEAKAGE BREAKDOWN IF $\lvert V_{DS}\rvert$ EXCEEDS V_{bkd}

MAX AT $V_{DS} = V_{GS} - V_T$

$I_D = \overline{\mu}_n C_O \frac{Z}{L}\left[(V_{GS}-V_T)^2 - \frac{(V_{GS}-V_T)^2}{2}\right]$

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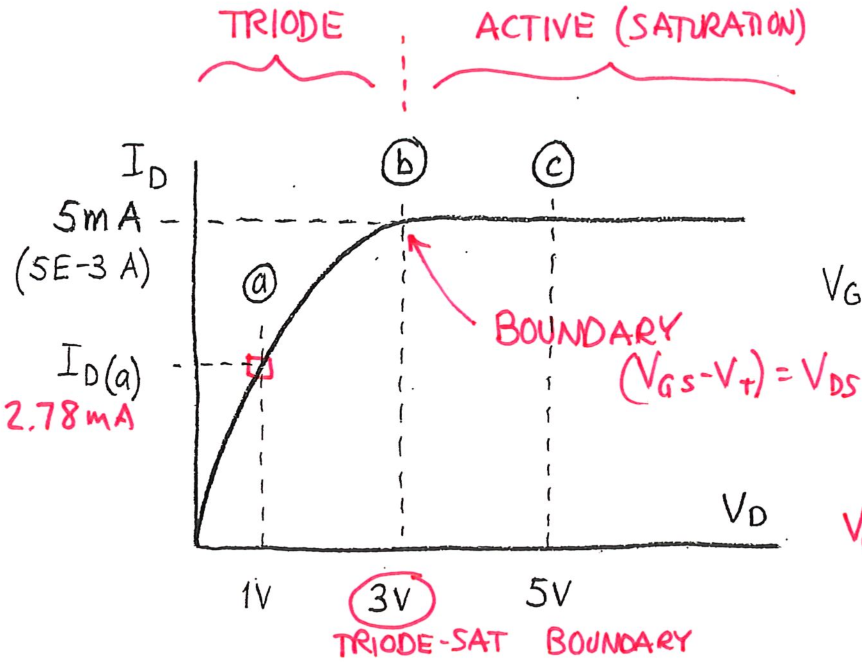
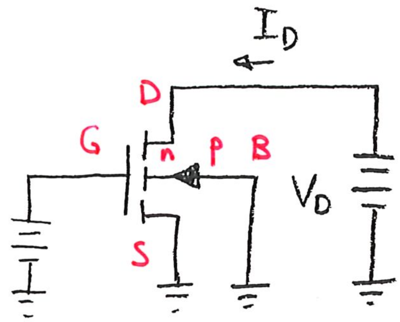




$V_T = +2V$

$V_{GS} - 2V = 3V \Rightarrow V_{GS} = 5V$

1) N-channel or P-channel?

2) If $V_T = +2V$, what is the applied gate voltage V_G? $\boxed{+5V}$

3) Sketch the channel charge configuration at (a), (b), and (c)

4) For operation at point (b): if the oxide thickness is x_0=0.2μm, determine the inversion charge layer density per unit area

- at the source end of the channel 5.18 E-8 coul/cm^2
- at the drain end of the channel 0 (channel pinched off)

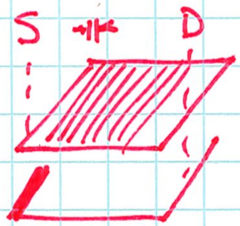
5) Determine $I_{D(a)}$, the drain current with $V_D = +1V$

TRIODE: $I_D = \underbrace{\bar{\mu}_n C_o \frac{Z}{L}}_{\text{GET FROM ACTIVE REGION}} \left[(V_{GS}-V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] = 1.11 \left[(3V)(1V) - \frac{(1V)^2}{2}\right]$

$= 2.78\,mA$

$$\underbrace{I_D}_{5mA} = \frac{\bar{\mu}_n C_o}{2} \frac{Z}{L} \underbrace{(V_{GS} - V_T)}_{3V}{}^2 \Rightarrow \bar{\mu}_n C_o \frac{Z}{L} = 1.11\, \frac{mA}{V^2}$$

PARALLEL PLATE CAP



$$\frac{\epsilon A}{d} \qquad \underbrace{\frac{\epsilon}{d}}_{\text{OXIDE CAP / UNIT AREA}} A$$

$X_o = 0.2\,\mu m$

$1\,\mu m = 1E\text{-}4\ CM$

$$\frac{K_{ox}\,\epsilon_0}{X_o} = \frac{(3.9)(8.85\,E\text{-}14\ F/cm)}{0.2\,E\text{-}4\ cm}$$

$$= 1.73\ E\text{-}8\ \frac{F}{CM^2}$$

AT SOURCE END

$Q = C\ V$

$C_G(V_G - V_T)$

$1.73\,E\text{-}8\,\frac{F}{CM^2}(5V - 2V) = 5.18^{E8}\ coul/CM^2$