ECE4902 Lecture 3

Finish from last time: MOSFET “building blocks”

Carrier Motion: Mobility

IC Passives:
Resistor
    Sheet Resistance; “Ω per square” concept
Capacitor

MOSFET as a switch
    “On” resistance R_{on}

MOSFET Operating Regions
    Cutoff
    Triode
    Active

MOSFET Square Law

Channel Length Modulation

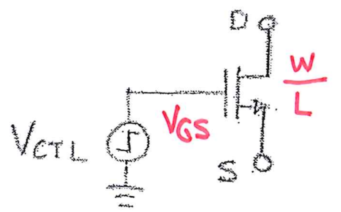
Hand in: HW 1

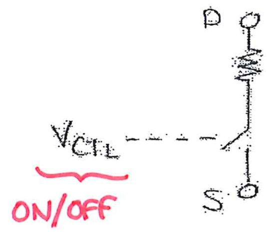
Handouts:
Lecture 3 Overview
Resistor, Capacitor
MOSFET cross section view
NMOS, PMOS Operating Regions
Operating Region Practice
Channel Length Modulation

MOSFET FUNCTIONS ("BUILDING BLOCKS")

GATE-SOURCE VOLTAGE CONTROLS DRAIN-SOURCE BEHAVIOR

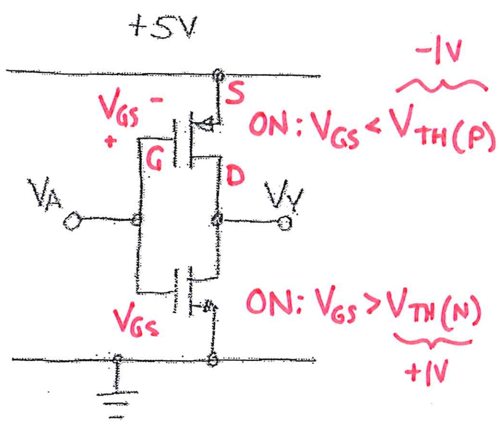
ANALOG SWITCH

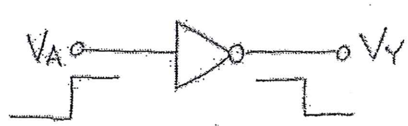




$$R_{on} = \frac{1}{\mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}$$

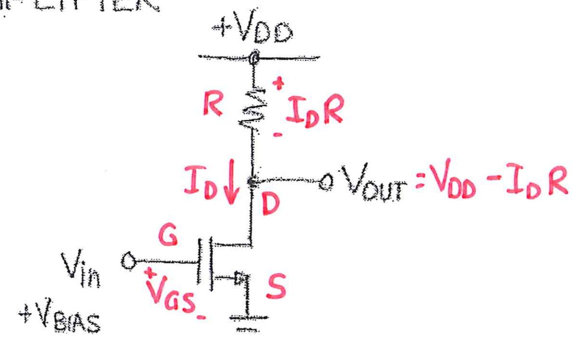
DIGITAL SWITCH CMOS INVERTER

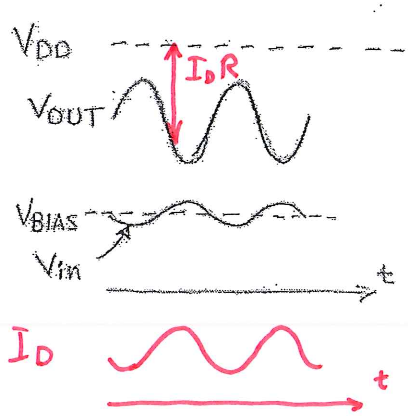




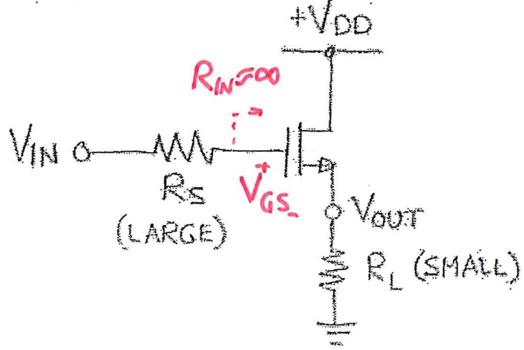
V_A	V_Y
+5V	0V
0V	+5V

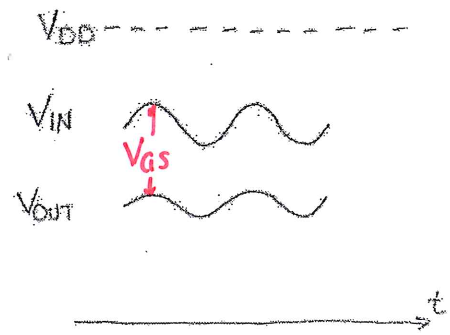
"COMMON SOURCE" AMPLIFIER



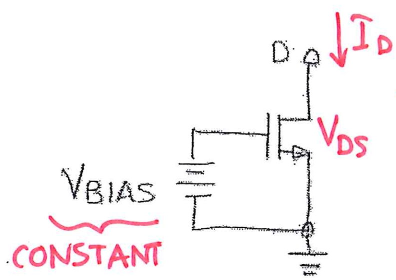


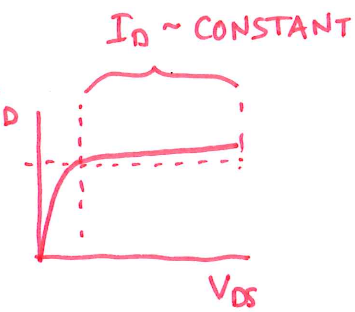
BUFFER/LEVEL SHIFTER

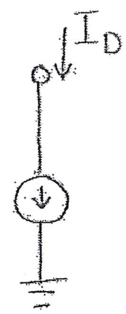




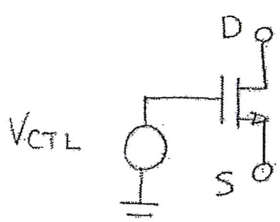
CURRENT SOURCE

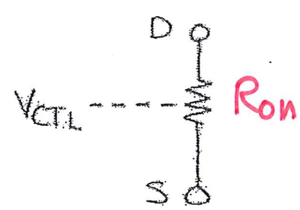






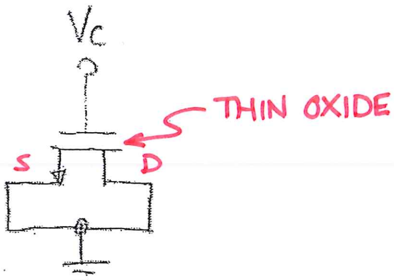
RESISTOR VOLTAGE CONTROLLED





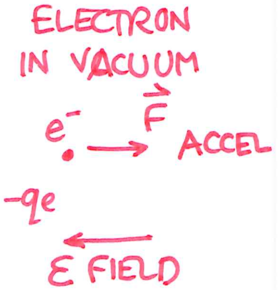
USED FOR
ELECTRICAL
CONTROL OF GAIN

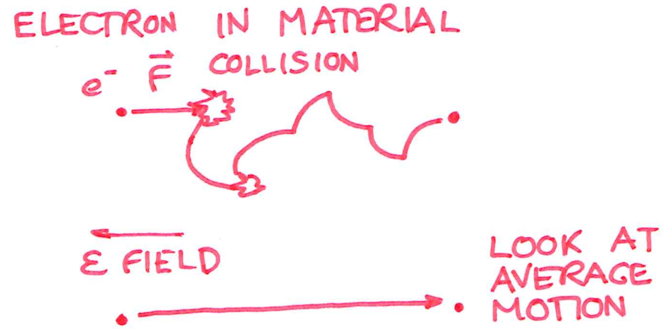
CAPACITOR

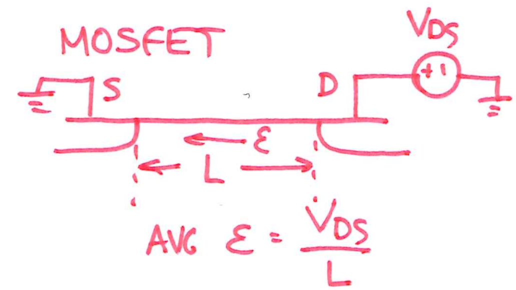


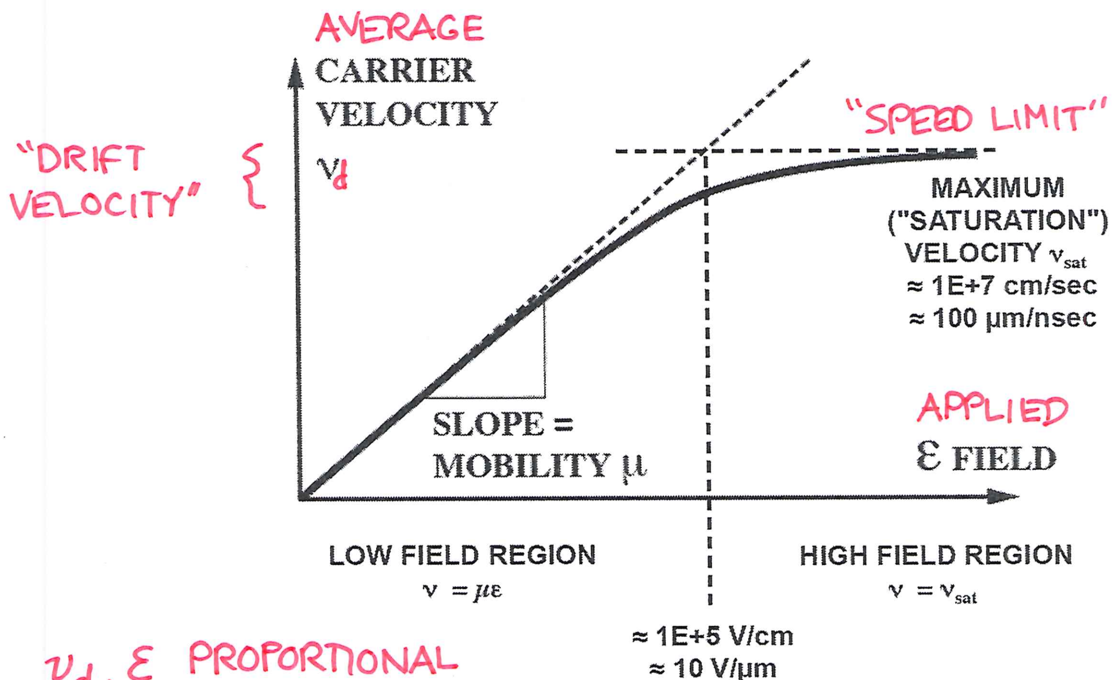
$$C = \frac{\varepsilon A}{d} \; \} t_{ox} \text{ THIN}$$

HIGH CAPACITANCE
VALUE / UNIT AREA









SHORT CHANNEL MOSFET: $L < 1\mu m$

v_d, ε PROPORTIONAL

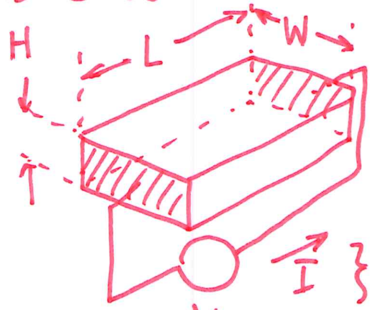
$$\boxed{\underbrace{v_d}_{\frac{cm}{sec}} = \mu \underbrace{\varepsilon}_{\frac{V}{cm}}}$$

$$[\mu] = \frac{cm^2}{V \cdot sec}$$

$e^- \approx 600\ cm^2/V\cdot sec$

hole $\approx 200\ cm^2/V\cdot sec$

WHAT IS THE RESISTANCE OF THIS BLOCK OF POLYSILICON?



$n \; \frac{\text{CARRIERS}}{\text{VOL}}$ MOBILE

I } WHAT I FLOWS FOR APPLIED V?

$\mathcal{E} = \frac{V}{L}$

DEF: $I = \frac{dQ}{dt}$ $\boxed{DC} \Rightarrow$ $I = \frac{\Delta Q}{\Delta t}$

ΔQ } TOTAL MOBILE CHARGE IN VOLUME

Δt } TIME FOR ALL CHARGE TO FLOW THROUGH → "LAST" CHARGE TO TRAVEL LENGTH L

$\underline{\underline{\Delta Q}}$

$$\underbrace{n}_{\frac{\cancel{CARR}}{\cancel{VOL}}} \; \underbrace{q_e}_{\frac{COUL}{\cancel{CARR}}} \; \underbrace{L\,W\,H}_{\cancel{VOL}} = \Delta Q \qquad [1]$$

Δt FROM DRIFT VELOCITY

$$v_d = \frac{L}{\Delta t} \Rightarrow \Delta t = \frac{L}{\underbrace{v_d}}$$

FROM MOBILITY $\quad = \mu \mathcal{E} = \mu \frac{V}{L}$

$$\Delta t = \frac{L^2}{\mu V} \qquad [2]$$

TOP VIEW

SIDE VIEW

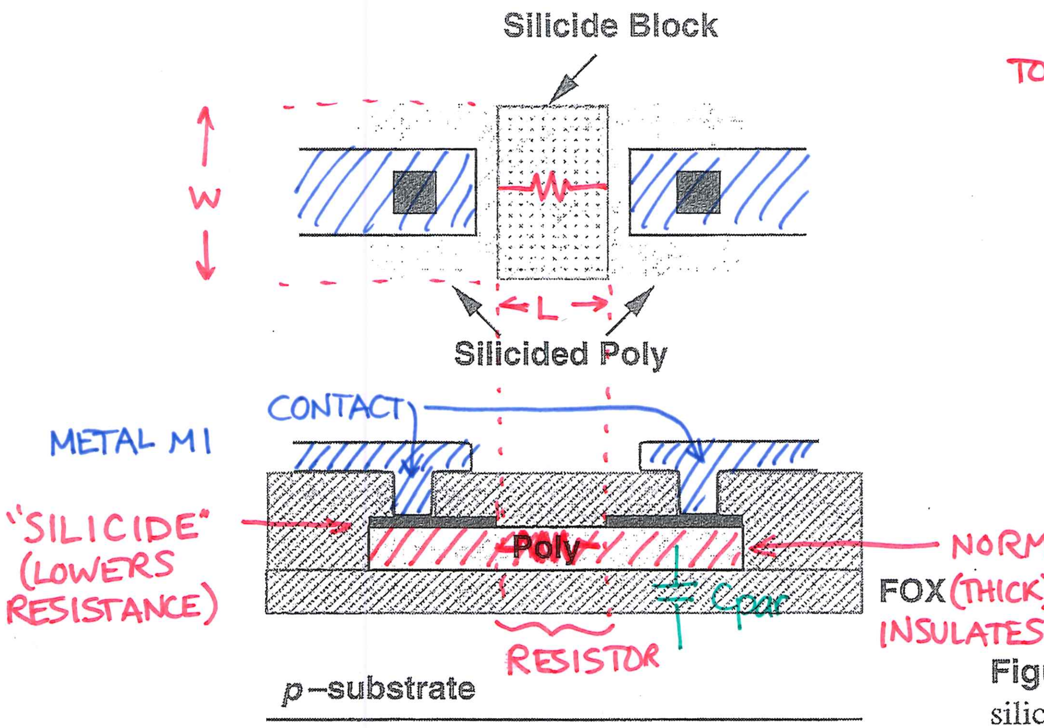
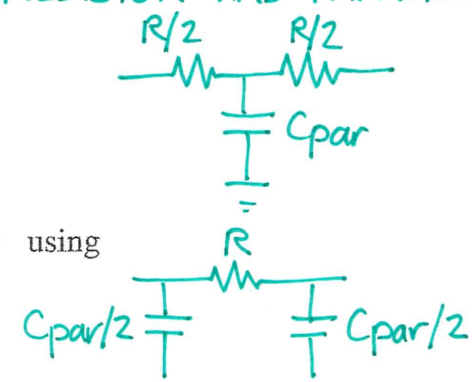


Figure 17.13 Poly resistor using silicide block.

RESISTOR HAS PARASITIC



SUB [1], [2] INTO I DEFINITION

$$I = \frac{\Delta Q}{\Delta t} = \frac{n q_e \cancel{L} W H \;\; \mu V}{L^{\cancel{2}}}$$

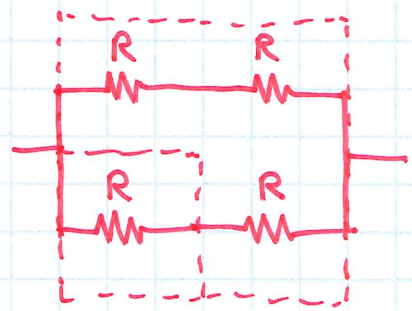
$$I = \underbrace{\left(\frac{n q_e W H \mu}{L} \right)}_{\substack{\text{V, I PROPORTIONAL:} \\ \text{RESISTANCE!}}} V$$

$$V = IR \Rightarrow R = \frac{V}{I} \Rightarrow R = \frac{L}{n q_e W H \mu} \xRightarrow[\text{REWRITE}]{} R = \underbrace{\overbrace{\left(\frac{1}{q_e n H \mu} \right)}^{\text{PROCESS}}}_{[\Omega]} \; \overbrace{\frac{L}{W}}^{\text{MASK}}$$

MASK: UNDER DESIGNER CONTROL

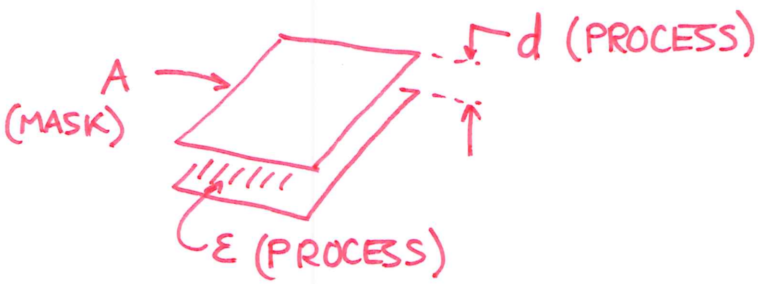
$\frac{L}{W}$: "ASPECT RATIO" (DIMENSIONLESS)

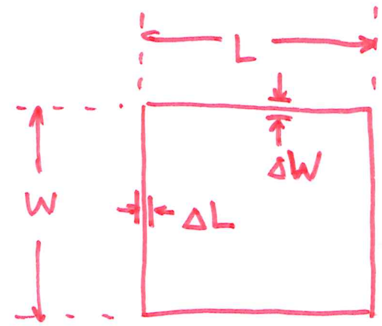
$[\Omega]$: "OHMS PER SQUARE" (SHEET RESISTANCE)



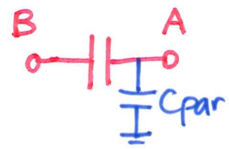
$2R \parallel 2R = R$

PARALLEL PLATE CAPACITANCE





$$C = \varepsilon \frac{A}{d} = \underbrace{\left(\frac{\varepsilon}{d}\right)}_{\frac{F}{\mu m^2}} \underbrace{A}_{MASK}$$



a 1E-18   1128 aF/µm²

f 1E-15   1.128 fF/µm²

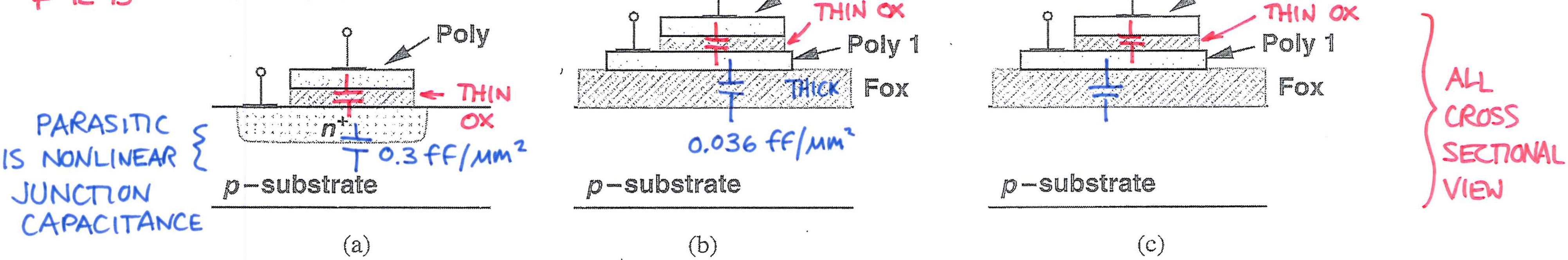
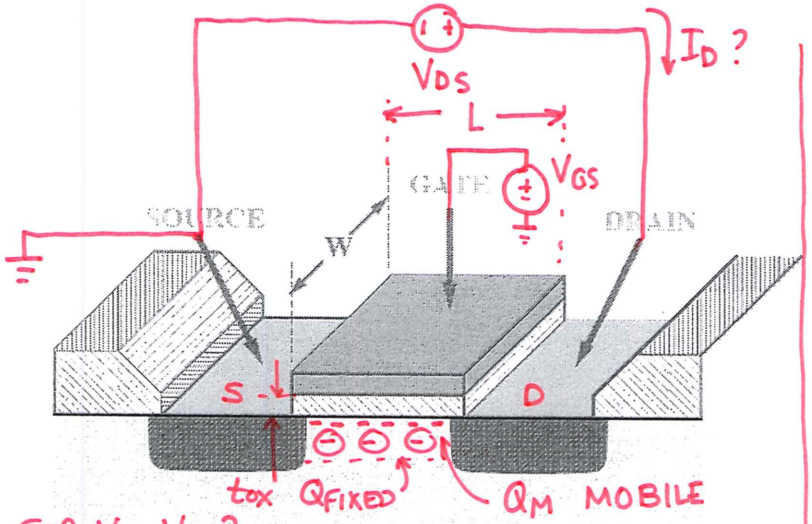


Figure 17.17 Linear capacitor structures, (a) poly-diffusion, (b) poly-poly, (c) metal-poly.



WHAT I_D FOR V_{GS}, V_{DS}?

DC: $I_D = \frac{\Delta Q}{\Delta t}$ } MOBILE CHARGE Q_M UNDER GATE
} LAST CHARGE TRAVEL S → D

$\underline{\Delta t}$ FROM "LAST" CHARGE

$v_d = \frac{L}{\Delta t} \Rightarrow \Delta t = \frac{L}{v_d}$ [1]

FROM MOBILITY $v_d = \mu \mathcal{E}$ [2]

FIELD: $\mathcal{E} = \frac{V_{DS}}{L}$ [3]

SUB [3] → [2] → [1]

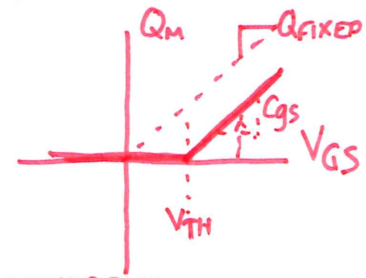
$\Delta t = \frac{L^2}{\mu V_{DS}}$ [4]

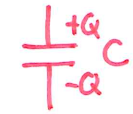
FAST? Δt SMALL

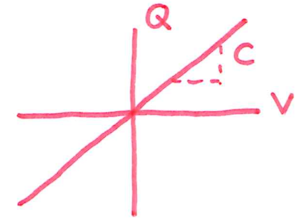
SHORT L GOOD FOR 2 REASONS

1. SHORTER DISTANCE
2. $\frac{V_{DS}}{L} = \mathcal{E}$ STRONGER FIELD
(UNTIL v_{sat})

$\underline{\Delta Q}$: MOSFET GATE CAP vs. PARALLEL PLATE







INVERSION LAYER

$Q_M = \underbrace{C_{gs}}(V_{GS} - V_{TH})$ [5]

$C = \varepsilon \frac{A}{d}$

PARALLEL PLATE GATE CAP

$\Delta Q = Q_M = C_{gs}(V_{GS} - V_{TH})$ [6]

FOR C_{gs}

$C_{gs} = \varepsilon \frac{A}{d} = \underbrace{K_o \varepsilon_o}_{\varepsilon \text{ OXIDE}} \frac{WL}{t_{ox}}$ } AREA A
} OXIDE THICKNESS [7]

REWRITE [7]

$C_{gs} = \underbrace{\left(\frac{K_o \varepsilon_o}{t_{ox}}\right)}_{\text{PROCESS}} \underbrace{WL}_{\text{MASK}}$ [8]

$\underbrace{\text{PROCESS}}$ C_{ox} GATE OXIDE $\frac{\text{CAPACITANCE}}{\text{UNIT AREA}}$

USING [8]

$C_{gs} = C_{ox} WL$ [9]

USE [9] IN [6] FOR ΔQ

$\Delta Q = C_{ox} WL (V_{GS} - V_{TH})$ [10]

SUB [4], [10] INTO I_D DEFINITION

$$I_D = \frac{\Delta Q}{\Delta t} = \frac{C_{ox} WL (V_{GS} - V_{TH})}{\frac{L^2}{\mu V_{DS}}}$$

} V_{GS} ONLY: GATE MAKES ΔQ MOBILE CHARGE

} V_{DS} ONLY: DRAIN MAKES CHARGE MOVE $S \to D$

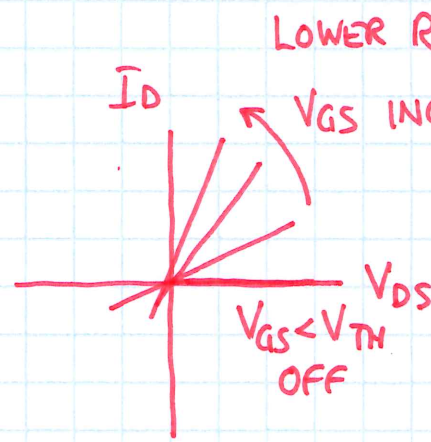
MASSAGE:

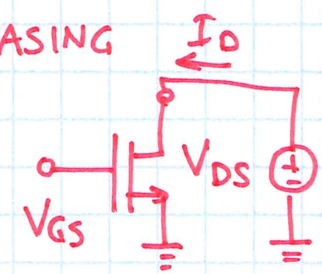
$$\underbrace{I_D}_{\text{DRAIN CURRENT}} = \underbrace{\mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})}_{\frac{1}{\text{RESISTANCE}}} \underbrace{V_{DS}}_{\text{DRAIN VOLTAGE}}$$

R_{on} "ON" RESISTANCE

$$R_{on} = \frac{1}{\underbrace{\mu C_{ox}}_{\text{PROCESS}} \underbrace{\frac{W}{L}}_{\substack{\text{MASK} \\ \text{GEOMETRY} \\ \text{(DESIGNER)}}} (\underbrace{V_{GS}}_{\substack{\text{APPLIED} \\ \text{GATE } V_{GS} \\ \text{ELECTRICAL} \\ \text{CONTROL}}} - V_{TH})}$$

PROCESS





ECE4902 N-CHANNEL MOSFET OPERATING REGIONS

GATE	DRAIN	REGION	FIRST ORDER BEHAVIOR	NOT EXACTLY:
$V_{GS} > V_{TH}$	$V_{DS} > V_{GS} - V_{TH}$	SATURATION (ACTIVE)	DRAIN "LOOKS LIKE" CURRENT SOURCE; I_D DEPENDS ONLY ON $V_{GS} - V_{TH}$ $$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_{TH})^2$$	CHANNEL LENGTH MODULATION I_D DEPENDS SOMEWHAT ON V_{DS} $$I_D = \frac{\mu_n C_{ox}}{2}\frac{W}{L}(V_{GS} - V_{TH})^2[1 + \lambda V_{DS}]$$
	$V_{DS} < V_{GS} - V_{TH}$	TRIODE	D-S CHANNEL "LOOKS" RESISTIVE $I_D = V_{DS} / R_{on}$ R_{on} DEPENDS ON $V_{GS} - V_{TH}$ $$R_{on} = \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})}$$	NONLINEAR AS V_{DS} INCREASES $$I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS} - V_{TH})V_{DS} - \underbrace{\frac{V_{DS}^2}{2}}_{\text{INTEGRAL}}\right]$$
$V_{GS} < V_{TH}$	$\lvert V_{DS}\rvert < V_{bkd}$	CUTOFF	SWITCH "OFF" $I_D = 0$	$I_D \approx$ pA to nA SUBTHRESHOLD CURRENT BREAKDOWN IF $\lvert V_{DS}\rvert$ EXCEEDS V_{bkd}