ECE4904 Lecture 11

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:
- Ch. 16, 17 figures

HW 5 due Thu 12/6

Critical Quantities:

MOS structure:
ϕ_F Flat Band potential
x_O Oxide thickness

Change with applied voltage:
ϕ_S Surface potential

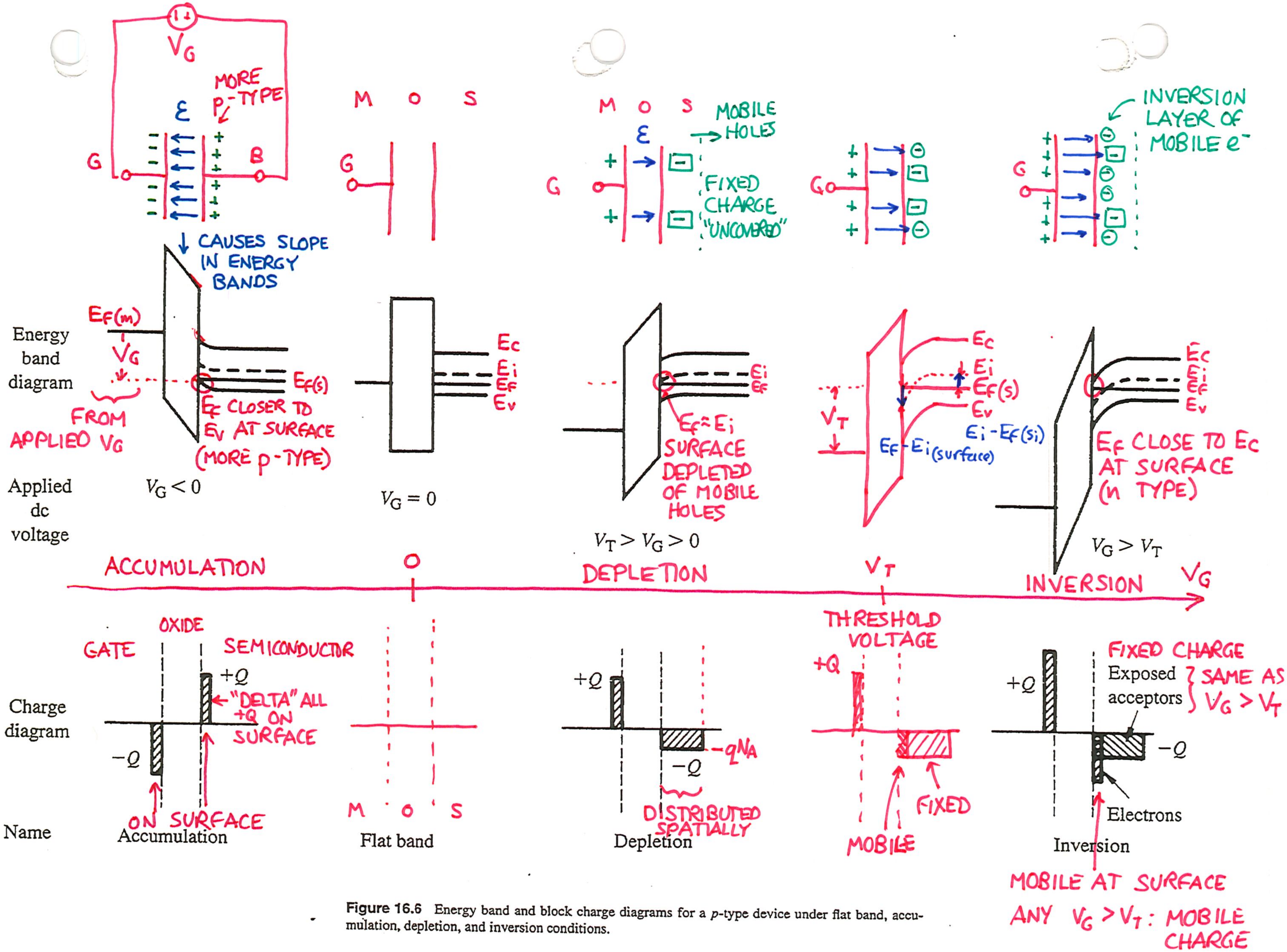

Figure 16.6 Energy band and block charge diagrams for a *p*-type device under flat band, accumulation, depletion, and inversion conditions.

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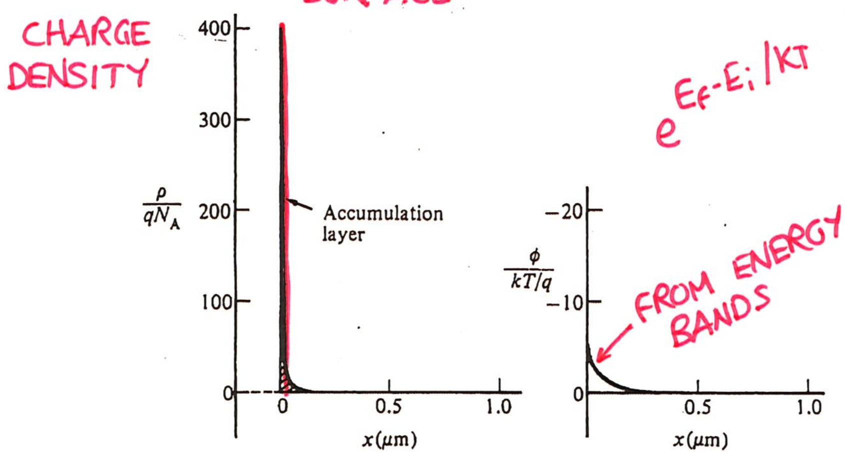
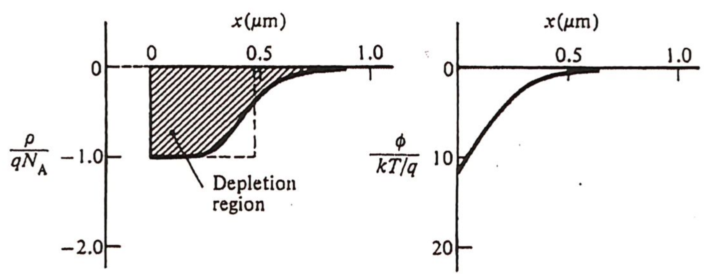
"DELTA DEPLETION APPROXIMATION"



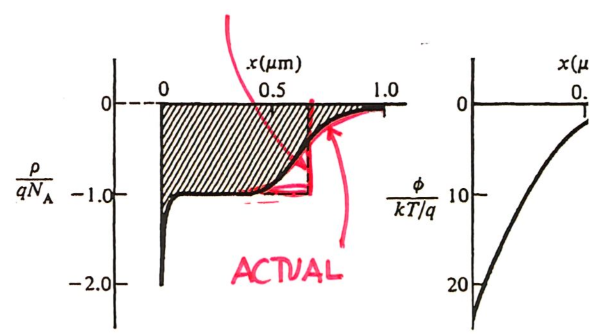
(a) Accumulation ($\phi_S = -6kT/q$)



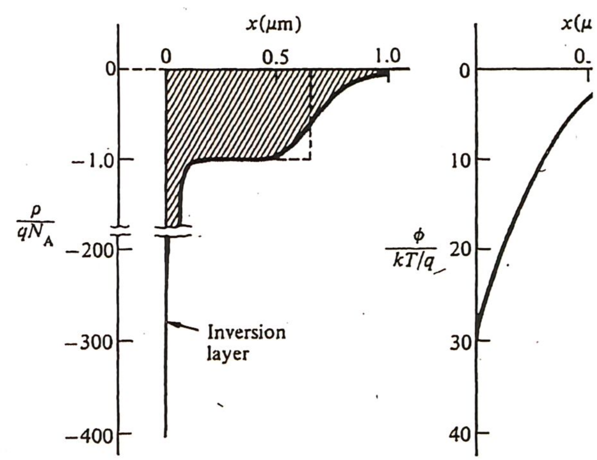
(b) Middle of depletion ($\phi_S = \phi_F = 12kT/q$)

Figure 16.8 Exact solution for the charge density and potential inside the semiconductor component of an MOS-C assuming $\phi_F = 12kT/q$ and $T = 300$ K ($kT/q = 0.0259$ V). (a) Accumulation ($\phi_S = -6kT/q$), (b) middle of depletion ($\phi_S = \phi_F = 12kT/q$), (c) onset of inversion ($\phi_S = 2\phi_F = 24kT/q$), and (d) heavily inverted ($\phi_S = 2\phi_F + 6kT/q = 30kT/q$). The ρ-diagrams were drawn on a linear scale and the $+\phi$ axes oriented downward to enhance the correlation with the diagrams sketched in Fig. 16.6. The dashed lines on the part (b) through (d) ρ-plots outline the depletion approximation version of the charge distribution.

DEPLETION APPROXIMATION



(c) Onset of inversion ($\phi_S = 2\phi_F = 24k$



(d) Deep into inversion ($\phi_S = 2\phi_F + 6kT/q$

Figure 16.8 *Continued.*

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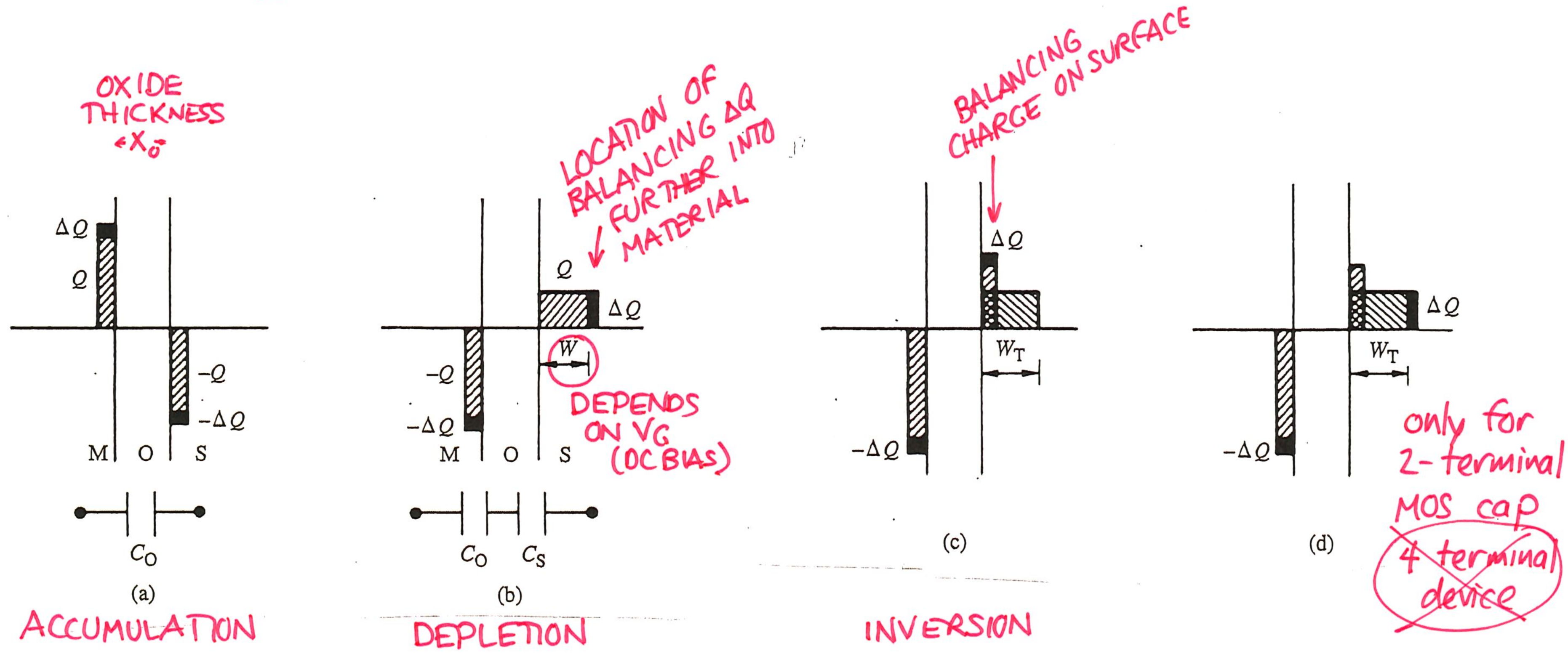
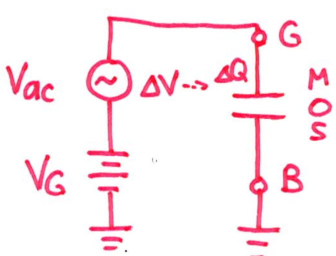
n SUBSTRATE



$$C = \frac{1}{\frac{1}{C_O} + \frac{1}{C_S}}$$



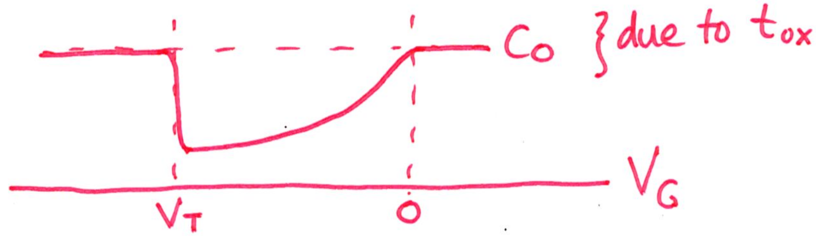


Figure 16.12 a.c. charge fluctuations inside an n-type MOS-capacitor under d.c. biasing conditions corresponding to (a) accumulation, (b) depletion, (c) inversion when $\omega \to 0$, and (d) inversion when $\omega \to \infty$. Equivalent circuit models appropriate for accumulation and depletion biasing are also shown beneath the block charge diagrams in parts (a) and (b), respectively.

$Q = CV$

$\Delta Q = C\Delta V$

$C_g = \frac{\Delta Q}{\Delta V}$

ECE4904 Threshold Voltage

Flat band voltage:

TELLS YOU IF SUBSTRATE IS p- OR n-TYPE

p-type bulk (NMOS)

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

n-type bulk (PMOS)

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

Threshold voltage:

$$V_T = \underbrace{2\phi_F}_{\text{INVERT Si AT OXIDE SURFACE}} + \overbrace{\frac{K_S}{K_O} x_O \sqrt{\frac{4qN_{SUB}}{K_S\varepsilon_0}\phi_F}}^{\text{VOLTAGE DROP IN OXIDE: GATE TO SURFACE}}$$

Substitute general expression for flat band voltage:

$$\phi_F = \frac{kT}{q} \ln\left(\frac{N_{SUB}}{n_i}\right)$$

Threshold voltage depends primarily on oxide thickness x_O, substrate doping N_{SUB}:

$$V_T = \frac{2kT}{q} \ln\left(\frac{N_{SUB}}{n_i}\right) + \frac{K_S}{K_O} \underbrace{x_O}_{} \sqrt{\frac{4kT\,N_{SUB}}{K_S\varepsilon_0} \ln\left(\frac{N_{SUB}}{n_i}\right)}$$

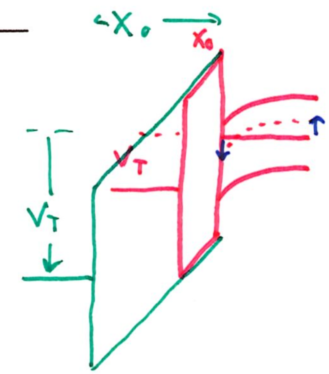
$N_{SUB} \uparrow \Rightarrow |V_T| \uparrow$

NEED TO DEPLETE HIGHER CONCENTRATION OF DOPANT ATOMS

OXIDE THICKNESS

$X_o \uparrow \Rightarrow |V_T| \uparrow$

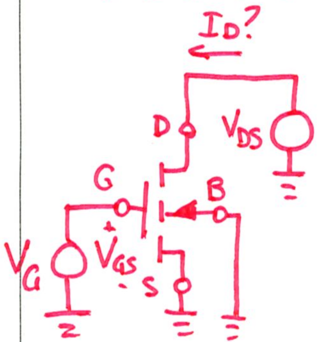
NEED MORE V_G TO GET NEEDED ϕ_S TO INVERT CHANNEL

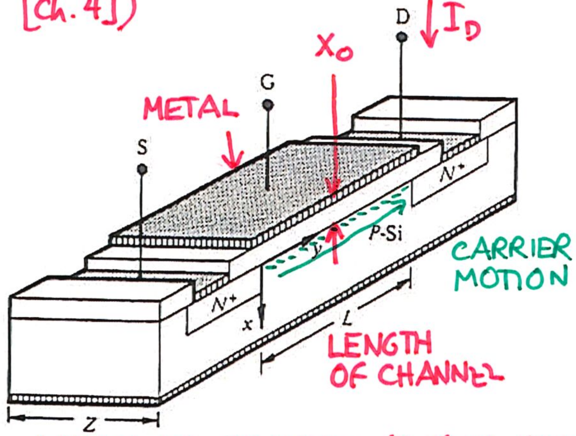


Z, L DETERMINED BY GATE GEOMETRY (MASK USED IN FABRICATION [Ch. 4])

PROCESS PARAMETER
$\overbrace{\text{OXIDE THICKNESS}}$

FOR ΔQ: WHEN WE APPLY V_G TO GATE HOW MUCH MOBILE CHARGE IN CHANNEL?

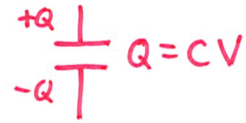


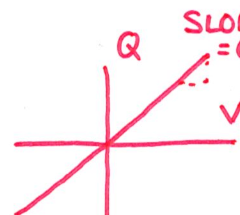


WIDTH OF CHANNEL ("W" IN 4902)

Figure 17.6 Device structure, dimensions, and coordinate orientations assumed in the quantitative analysis.

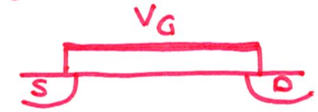
IDEAL CAP

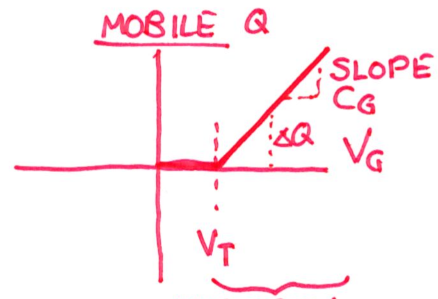




$C = \epsilon \frac{A}{d}$

MOS CAPACITOR





INVERSION LAYER

START: DC CURRENT $I_D = \frac{\Delta Q}{\Delta t}$ } ALL MOBILE CHARGE IN CHANNEL } TIME S → D

GATE OXIDE CAPACITANCE

$$C_G = \epsilon \frac{A}{d} = K_o \epsilon_o \frac{ZL}{x_o}$$

Δt FROM VELOCITY $v = \frac{L}{\Delta t} = \underbrace{\mu}_{\text{MOBILITY}} \mathcal{E}$ $\quad \underbrace{\mathcal{E} = \frac{V_{DS}}{L}}_{\text{HORIZONTAL } \mathcal{E} \text{ FIELD}} \Rightarrow \Delta t = \frac{L^2}{\mu V_{DS}}$

$$C_G = \underbrace{\frac{K_o \epsilon_o}{x_o}}_{C_o} \underbrace{ZL}_{\text{AREA OF GATE}}$$

GATE OXIDE CAPACITANCE / UNIT AREA

$$\underbrace{I_D}_{\text{DRAIN CURRENT}} = \frac{\Delta Q}{\Delta t} = \frac{C_o Z \cancel{L} (V_G - V_T) \mu V_{DS}}{L^{\cancel{2}}} \text{ } \} \text{ DRAIN VOLTAGE}$$

MOBILE CHARGE IN CHANNEL:

$$\Delta Q = C_o Z L \underbrace{(V_G - V_T)}$$

ONLY $V_G > V_T$ MAKES MOBILE e^- IN CHANNEL

"ON" RESISTANCE $\boxed{\frac{V_{DS}}{I_D} = \frac{1}{\mu C_o \frac{Z}{L} (V_{GS} - V_T)}}$ $\quad r_{ds(on)} \to 0$

HIGHER μ, $\mu_n > \mu_p$
$K_o \epsilon_o$ HIGH K_o DIELEC
x_o THIN OXIDE
SIZE WIDE SHORT
V_{GS} HIGHER

$V_G < V_T$ CUTOFF $I_D = 0$

$V_G > V_T$