Chapter 17.

MOSFETs - An Introduction

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Qualitative Theory of Operation

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  - **MOSFET=MOS-Capacitor + 2 pn junctions**
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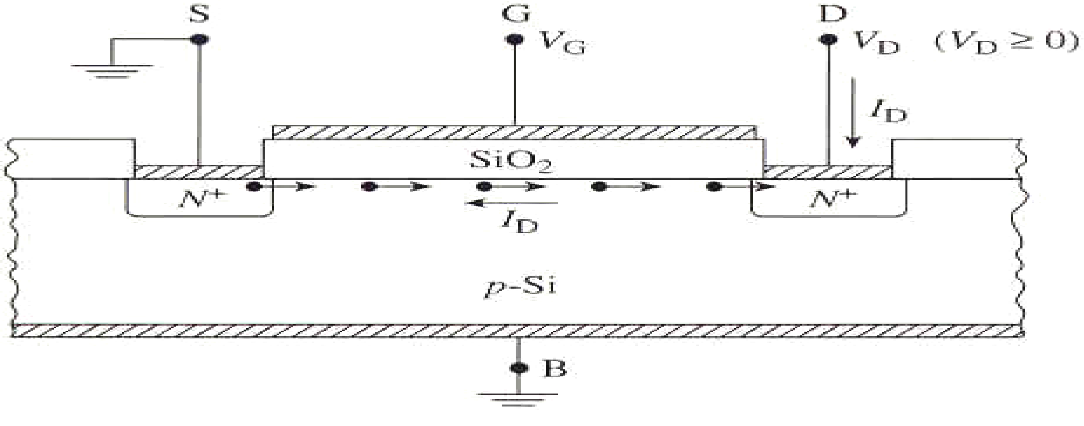
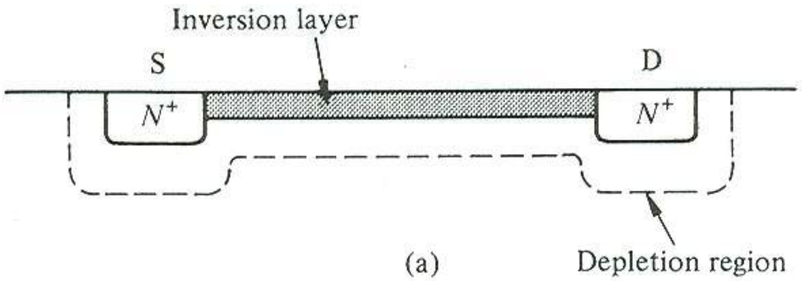
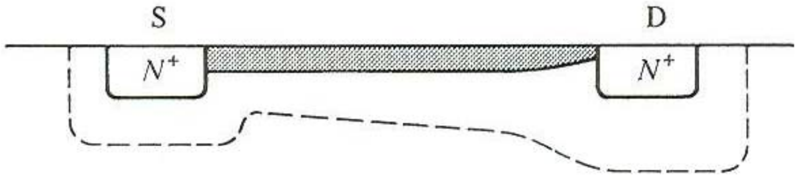


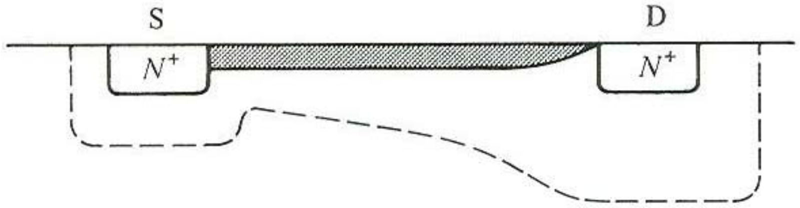
(b)


Inversion layer
S
D
N^+
N^+
Depletion region

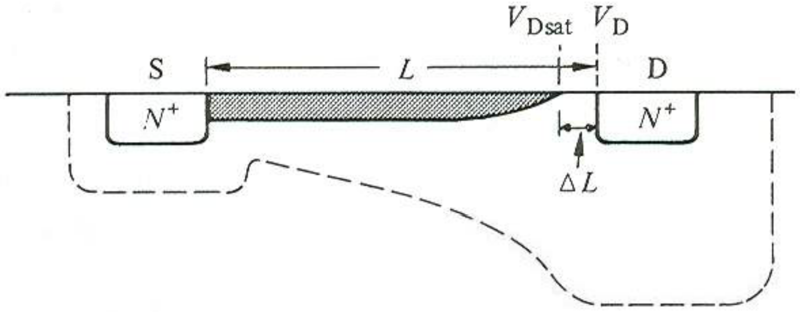
(a)


S
D
N^+
N^+

(b)


S
D
N^+
N^+

(c)


V_{Dsat}
V_{D}
S
L
D
N^+
N^+
ΔL

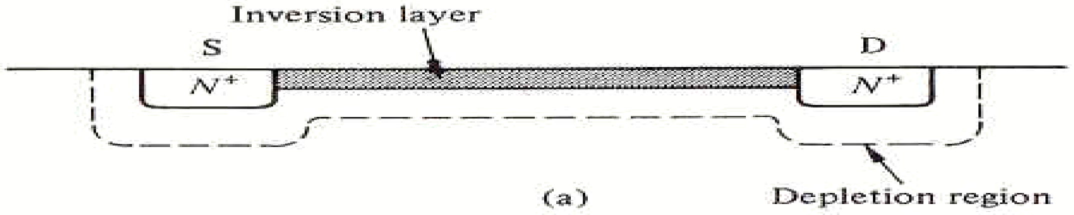
(d)

$V_D = 0$ Case

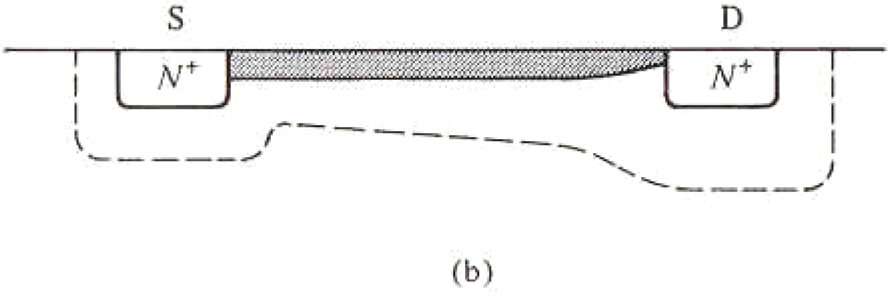
- When $V_G \leq V_T$, very few electrons in the channel. ⇒ an open circuit between the n+ region
- When $V_G > V_T$,
  - Inversion layer is formed
  - The conducting channel (induced “n-type” region, inversion layer) connects the D & S
  - V_G↑ ↙ the pile up of electrons↑ ↙ conductance ↑

$\therefore$ V_G determines the maximum conductance

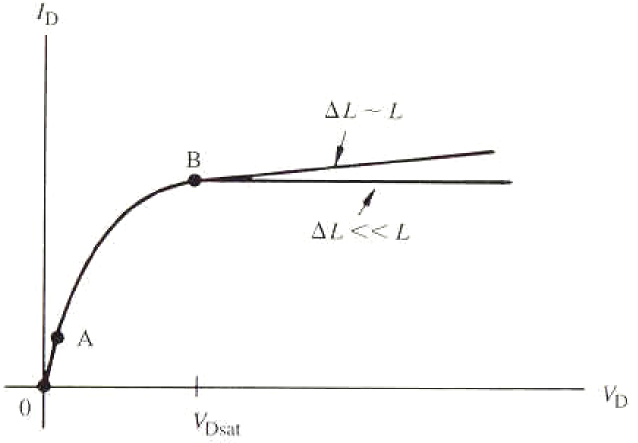
  - Thermal equilibrium prevails, and I_D=0



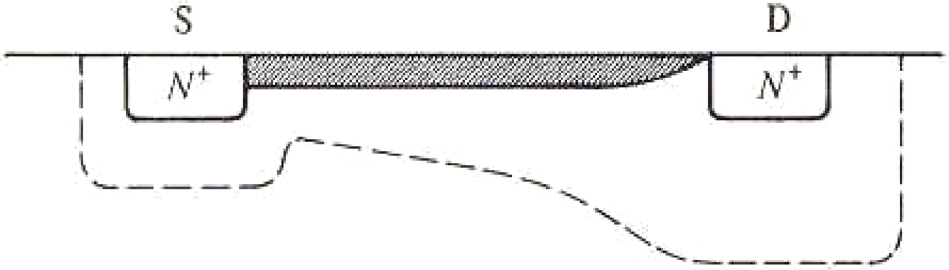
- **The V_D is increased in small steps starting from $V_D = 0$**
  - **The channel acts like a simple resistor**
  - **$I_D \propto V_D$**
  - **The reverse bias junction current is negligible**
  - **voltage drop from the drain to the source starts to negate the inverting effect of the gate**
  - **$V_D\uparrow$ ⇙Depletion of the channel↑ ⇙# of carriers↓⇙ conductance↓ ⇙ slope-over in the *IV***

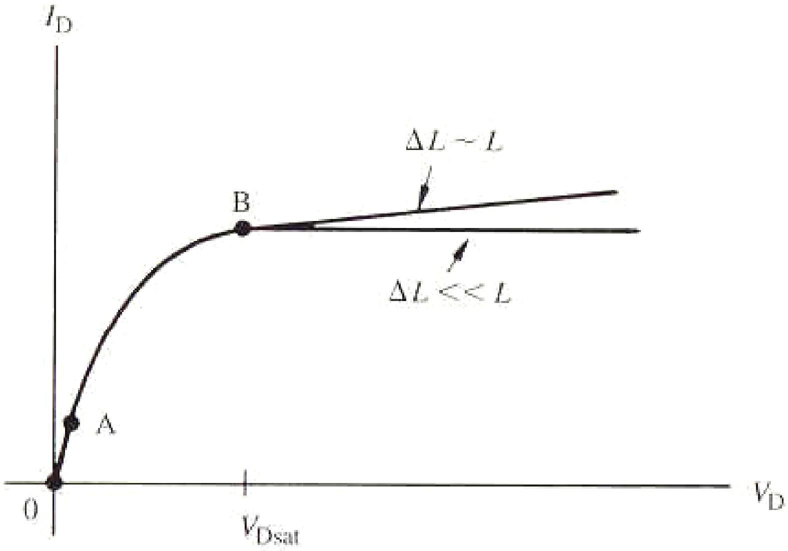


(b)

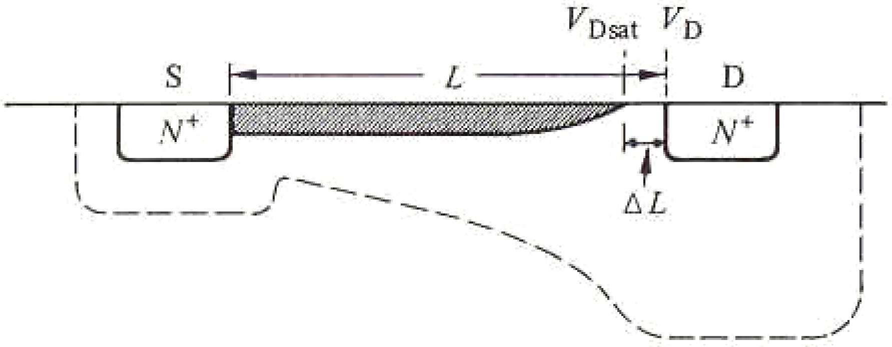


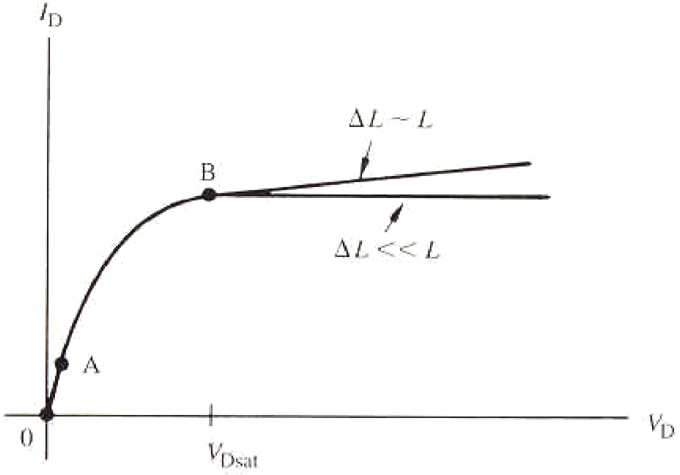
- **Pinch - off ($V_D = V_{Dsat}$)**
  - **Disappearance of the channel adjacent to the drain**
    - **The slope of the I_D-V_D becomes approximately zero(Point B)**





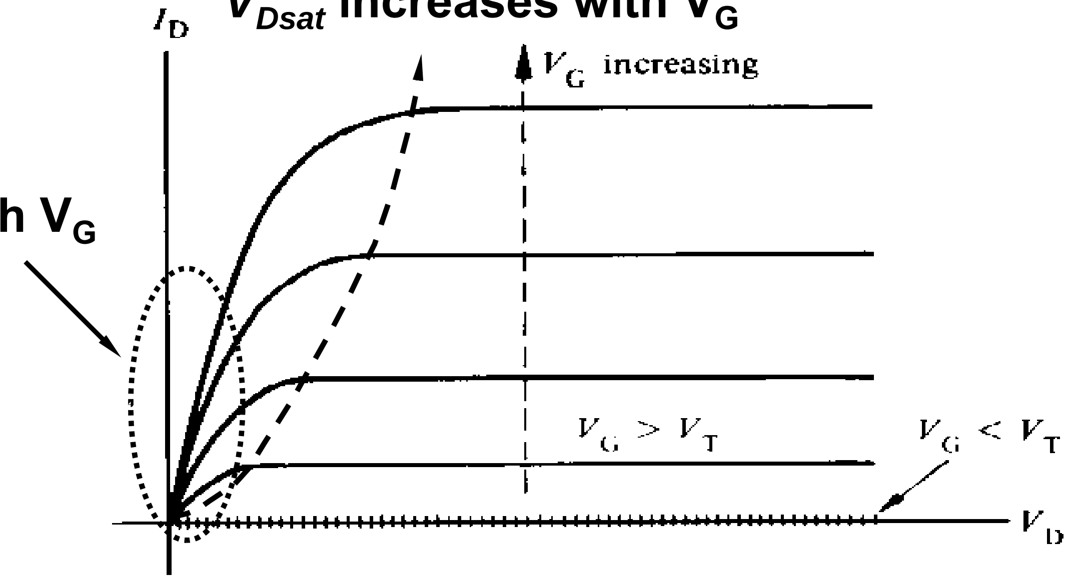
- **Post-pinch-off ($V_D > V_{Dsat}$)**
  - **The pinched-off portion widens from just a point into a depleted channel section ΔL**
  - **The pinched-off section absorbs most of the voltage drop in excess of V_{Dsat}**
  - **For $\Delta L << L$, the shape of the conducting region and the potential across the region do not change ⇙Constant I_D**
  - **For $\Delta L \sim L$, I_D will increase with $V_D > V_{Dsat}$**





I_D - V_D Characteristics

- General form of the I_D - V_D ($\Delta L << L$)
  - For $V_G \leq V_T$, $I_D \approx 0$
  - For $V_G > V_T$, transistor action: I_D is modulated by V_G
  - $V_D > V_{Dsat}$: saturation region
  - $V_D < V_{Dsat}$: linear(triode) region



V_{Dsat} increases with V_G

The slope increases with V_G

MOSFETs – An Introduction

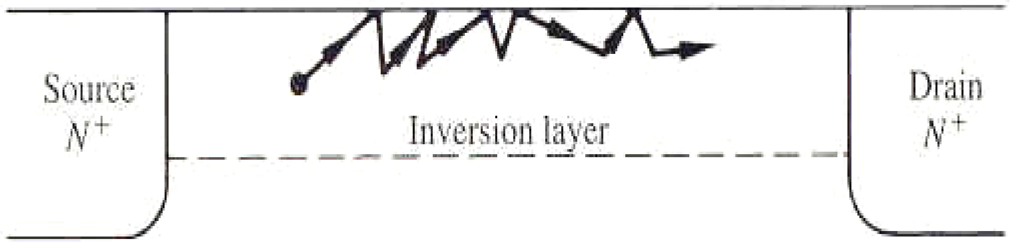
Quantitative I_D - V_D Relationships

- **Effective Mobility**

  : Impurity Scattering

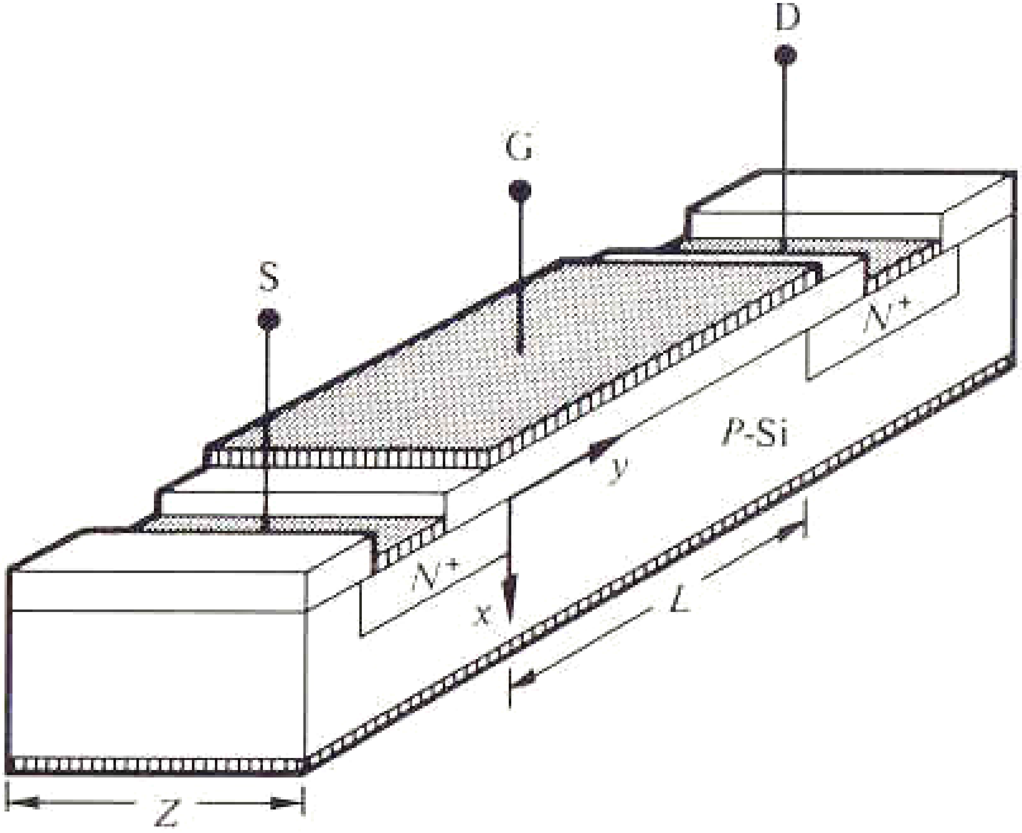
  + Lattice Scattering

  + Surface Scattering

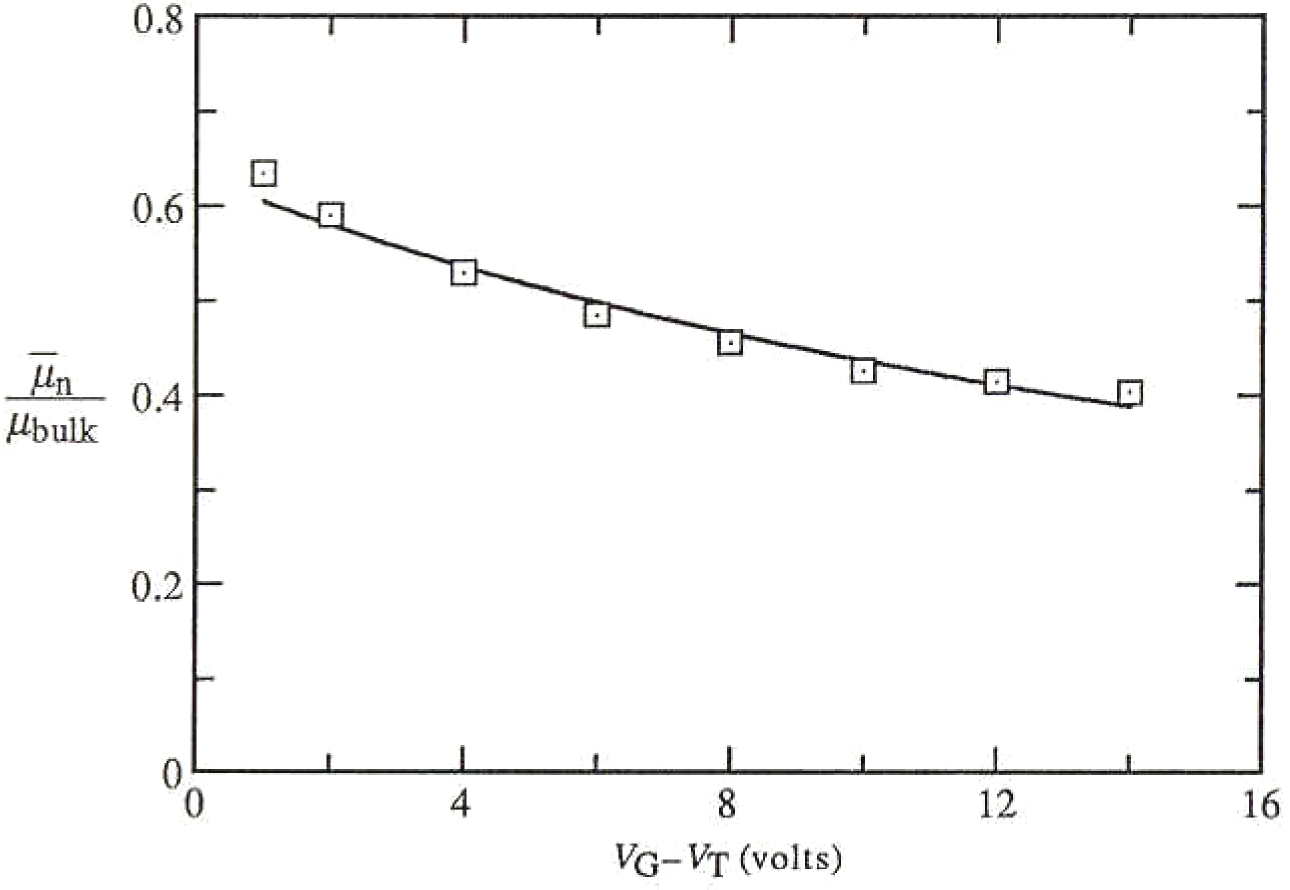


- **Effective Mobility**

$$\overline{\mu_n} = \frac{\int_0^{x_c(y)} \mu_n(x,y)n(x,y)dx}{\int_0^{x_c(y)} n(x,y)dx}$$



$$-\ V_G \uparrow \rightarrow \left\{\begin{array}{l}\text{more carriers closer to the interface}\\ \text{higher electric field}\end{array}\right\} \begin{array}{l}\rightarrow \text{surface scattering} \uparrow\\ \rightarrow \bar{\mu}_n \downarrow\end{array}$$



- **Square - Law Theory**
  - $V_D < V_{Dsat}$
    - **A drift current is dominant**

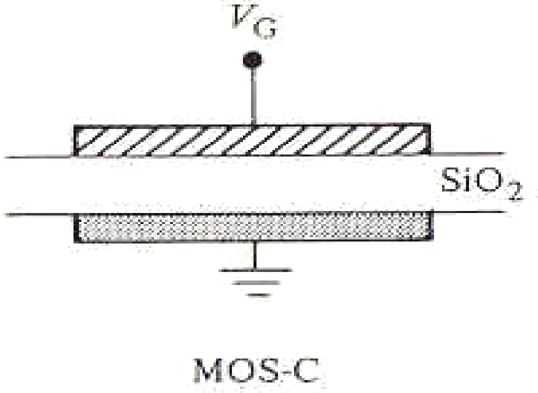
$$Q_{gate} = -Q_{semi} \cong -Q_N$$

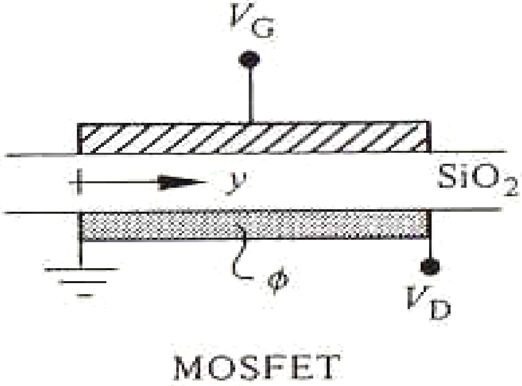
$$Q_N \cong -C_o(V_G - V_T)$$

At an arbitrary point y

$$Q_N(y) \cong -C_o(V_G - V_T - \phi) \rightarrow I_D = -WQ_N(y)\bar{\mu}_n E(y)$$

$$= W\bar{\mu}_n C_o(V_G - V_T - \phi)\frac{d\phi}{dy}$$





Integrating

$$\int_0^L I_D dy = W\overline{\mu}_n C_o \int_0^{V_D} (V_G - V_T - \phi) d\phi$$

$$\rightarrow I_D = \frac{W\overline{\mu}_n C_o}{L}\left[(V_G - V_T)V_D - \frac{{V_D}^2}{2}\right]$$

- $V_D \geq V_{Dsat}$
  - I_D **is approximately constant**

$$I_{Dsat} = \frac{W\overline{\mu}_n C_o}{L}\left[(V_G - V_T)V_{Dsat} - \frac{V_{Dsat}^{\,2}}{2}\right]$$

$$Q_N(L) = -C_o(V_G - V_T - V_{Dsat}) = 0$$

$$\boxed{V_{Dsat} = V_G - V_T}$$

$$\boxed{I_{Dsat} = \frac{W\overline{\mu}_n C_o}{2L}(V_G - V_T)^2}$$

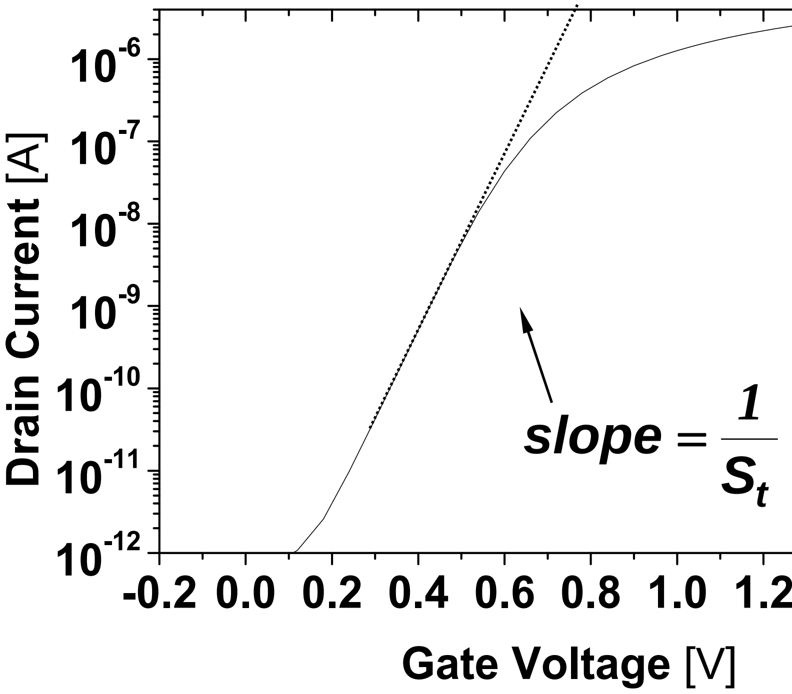
- **Subthreshold transfer characteristics**
  - **At weak inversion, diffusion current dominates**

$$I \approx I_{diff} \propto \frac{Q_S\text{-}Q_D}{L} \propto \frac{Q_S}{L}\left[1 - exp(-\frac{qV_D}{kT})\right]$$

where $Q_D = Q_S\, exp\left(-\frac{qV_D}{kT}\right)$

where Q_S **is exponential function of** V_G

  - **In long channel MOSFETS the subthreshold current varies exponentially with V_G and is independent of V_D provided $V_D >$ a few kT/q**



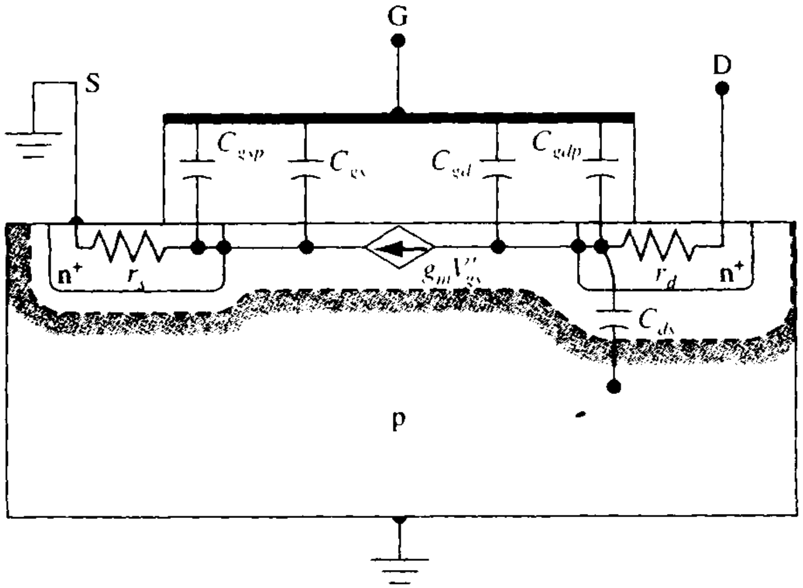
Subthreshold swing

$$S_t = \frac{1}{\dfrac{d \log I_D}{dV_G}} \ [mV/dec]$$

$$= \text{change in } V_G$$

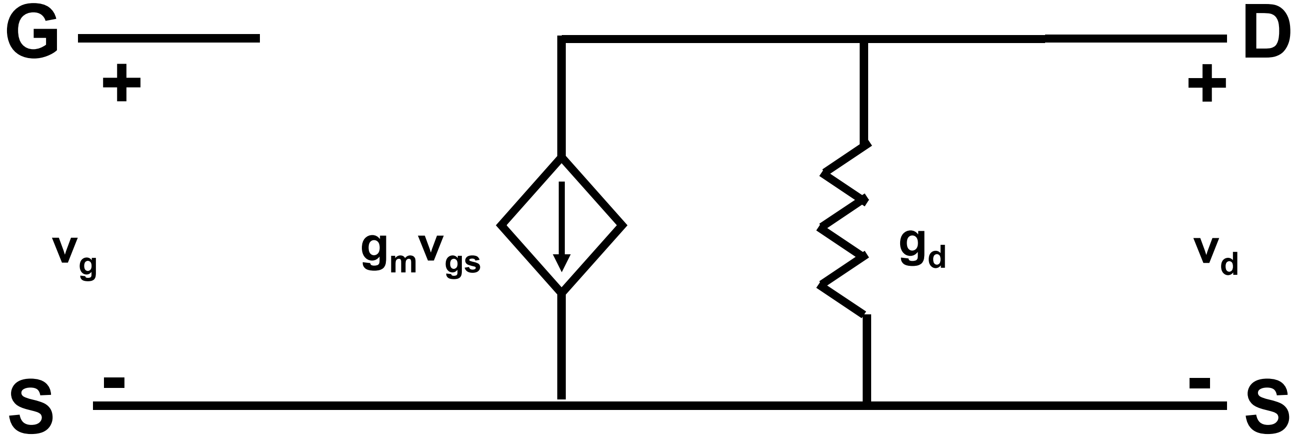
$$\text{for a decade change in } I_D$$

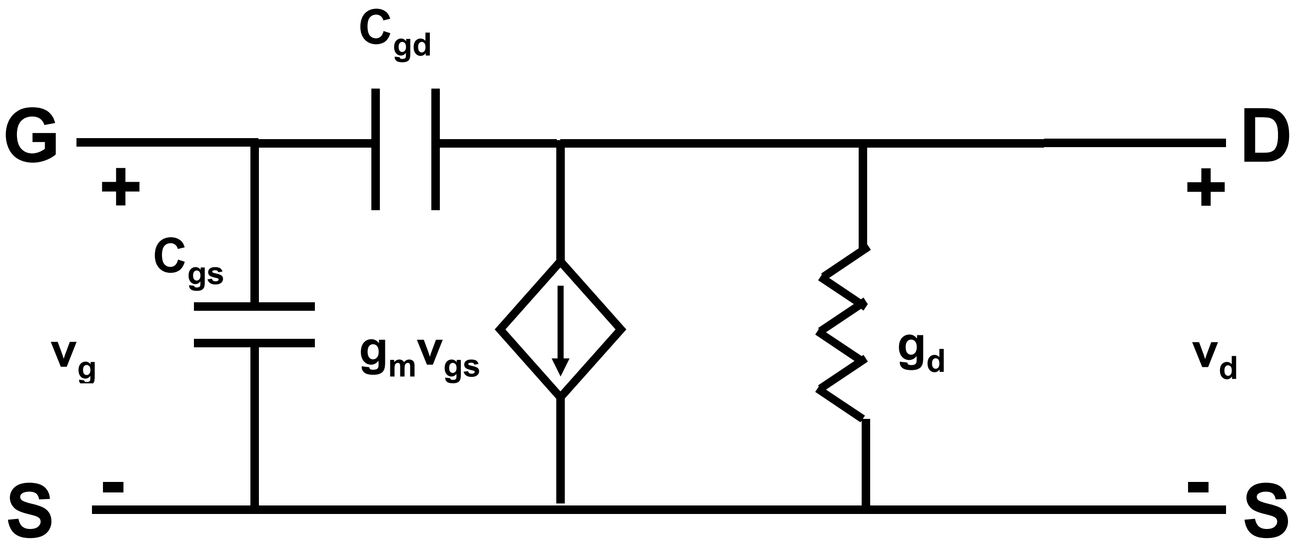
17.3 a.c. Response(skip)



- C_{gs}(C_{gd}): The interaction between G and the channel charge near S(D)
- C_{gsp},C_{gdp}: parasitic or overlap capacitances

- **Small-signal equivalent circuit**





- **A capacitor behaves like an open circuit at low frequencies.**

- $I_D(V_D,V_G) + i_d = I_D(V_D + v_d\ ,\ V_G + v_g)$
- $i_d = I_D(V_D + v_d\ ,\ V_G + v_g) - I_D(V_D,V_G)$

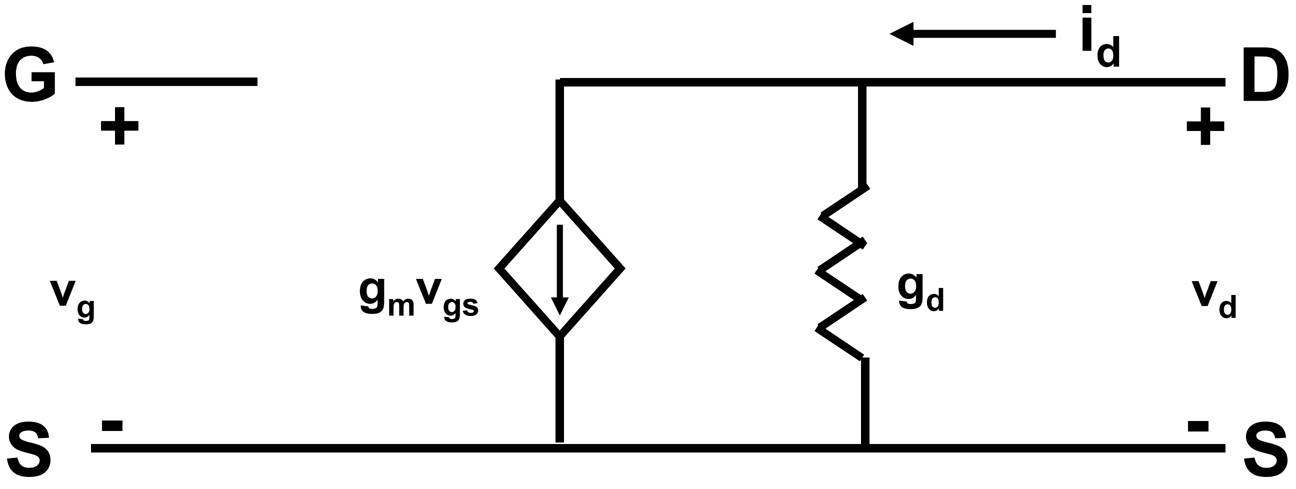
$$I_D\left(V_D + v_d, V_G + v_g\right) = I_D\left(V_D, V_G\right) + \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G} v_d + \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D} v_g$$

$$\therefore i_d = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G} v_d + \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D} v_g$$

$$g_d = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G = \text{constant}} \quad \cdots \textit{the drain or channel conductance}$$

$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D = \text{constant}} \quad \cdots \textit{transconductance or mutual conductance}$$

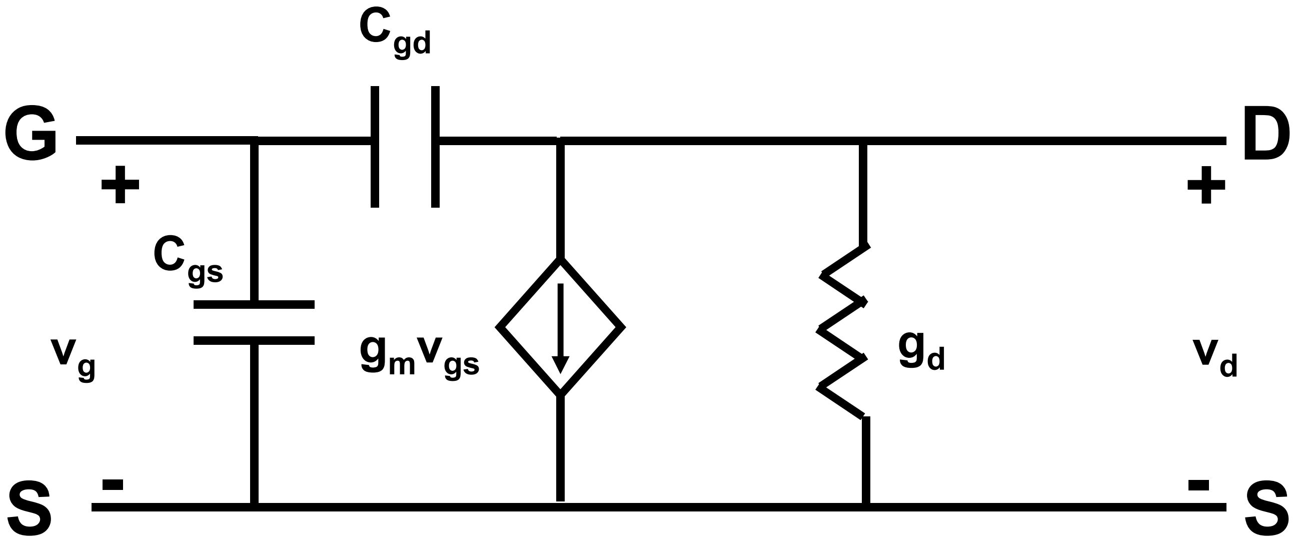
$$\therefore i_d = g_d v_d + g_m v_g$$



- Table 17.1

	Below pinch-off ($V_D \le V_{Dsat}$)	Above pinch-off ($V_D > V_{Dsat}$)
	$g_d = \frac{Z\overline{\mu_n}C_O}{L}(V_G - V_T - V_D)$	$g_d = 0$
	$g_m = \frac{Z\overline{\mu_n}C_O}{L}V_D$	$g_m = \frac{Z\overline{\mu_n}C_O}{L}(V_G - V_T)$

- At the higher operational frequencies encountered in practical applications, the circuit must be modified to take into account capacitive coupling between the device terminals.
- The overlap capacitance is minimized by forming a thicker oxide in the overlap region or preferably through the use of self aligned gate procedures. ➔ C_{gd} is typically negligible.



- ## 17.3.2. Cutoff Frequency

The f_T be defined as the frequency where the MOSFET is no longer amplifying the input signal under optimum conditions.
→ Value of the output current to input current ratio is unity

$$i_{in} = jw(C_{gs} + C_{gd})v_g \cong j(2\pi f)C_o v_g$$

$$i_{out} \approx g_m v_g$$

$$\left| i_{out} / i_{in} \right| = 1$$

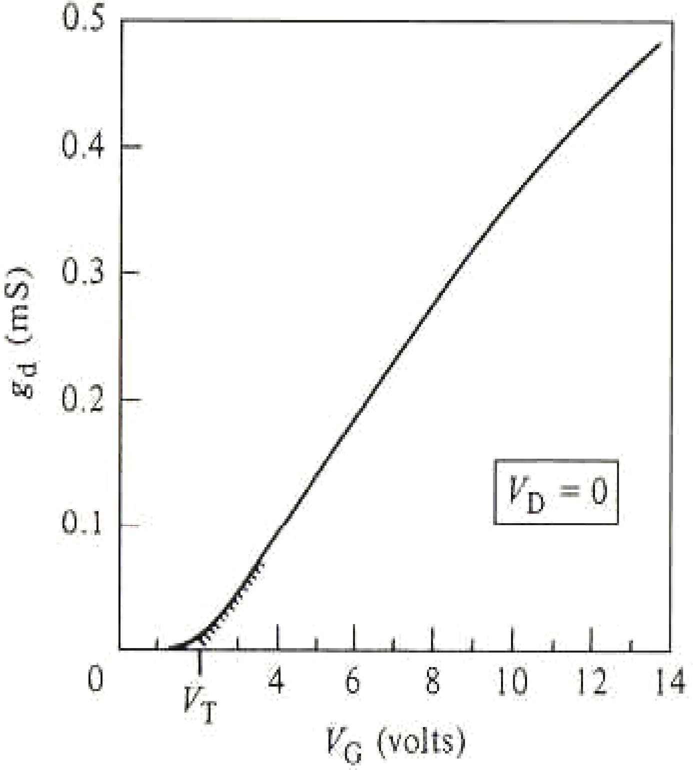
$$\therefore\ f_T = \frac{g_m}{2\pi C_o} = \frac{\overline{\mu_n} V_D}{2\pi L^2} \qquad if\ V_D \le V_{Dsat}$$

Small Signal Characteristics

- g_d vs. $V_G(V_D=0)$
  - Extrapolating the linear portion of the g_d-V_G characteristics into the V_G axis and equating the voltage intercept to V_T

$$g_d=\frac{W\bar{\mu}_n C_o}{L}(V_G-V_T)\ \ (V_D=0)$$

  - Deduce the effective mobility from the slope



- Gate Capacitance vs. V_G (V_D=0)
  - Diagnostic purposes in much the same manner as the MOS-C C-V_G characteristics
  - Unlike the MOS-C , a low-frequency characteristics is observed even for frequencies exceeding 1MHz
    - Because the source and drain islands supply the minority carries