Chapter 6 MOSFET in the On-state

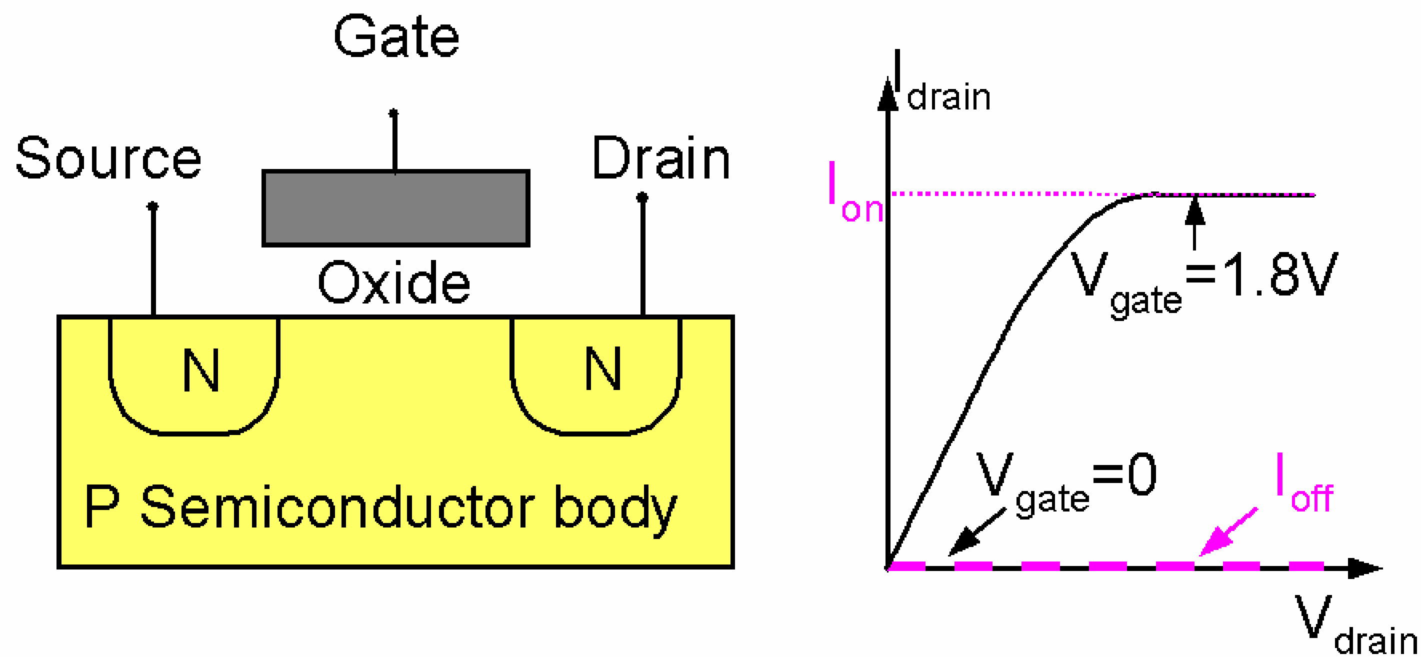
The MOSFET (MOS Field-Effect Transistor) is the building block of Gb memory chips, GHz microprocessors, analog, and RF circuits.

Match the following MOSFET characteristics with their applications:

- small size
- high speed
- low power
- high gain

6.1 Introduction to the MOSFET

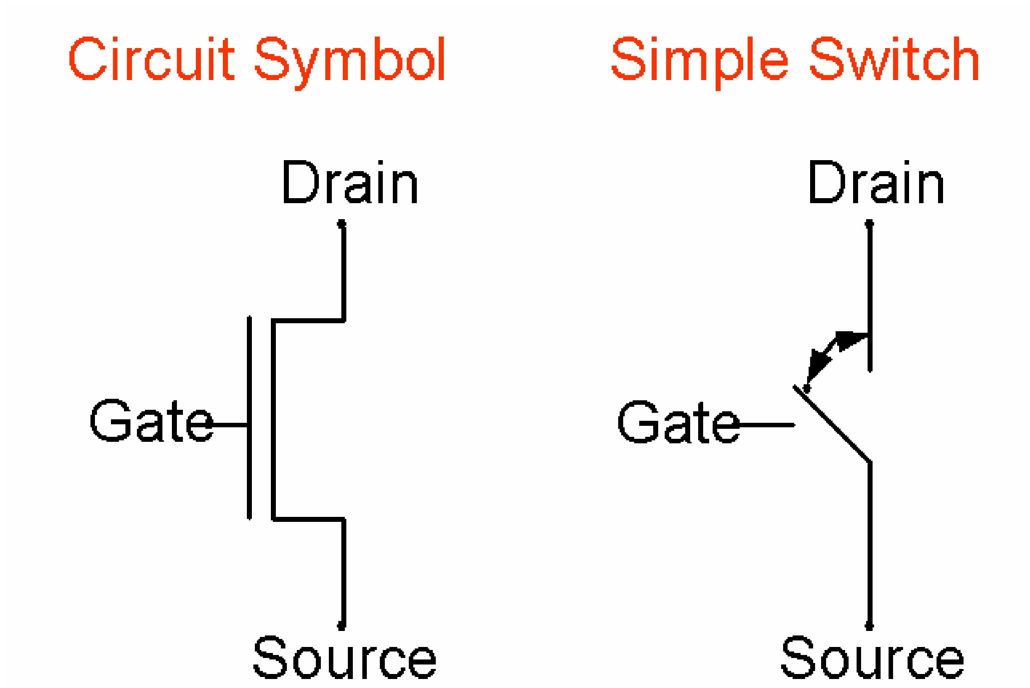
Basic MOSFET structure and IV characteristics



What is desirable: large I_{on}, small I_{off}

6.1 Introduction to the MOSFET

Two ways of representing a MOSFET:



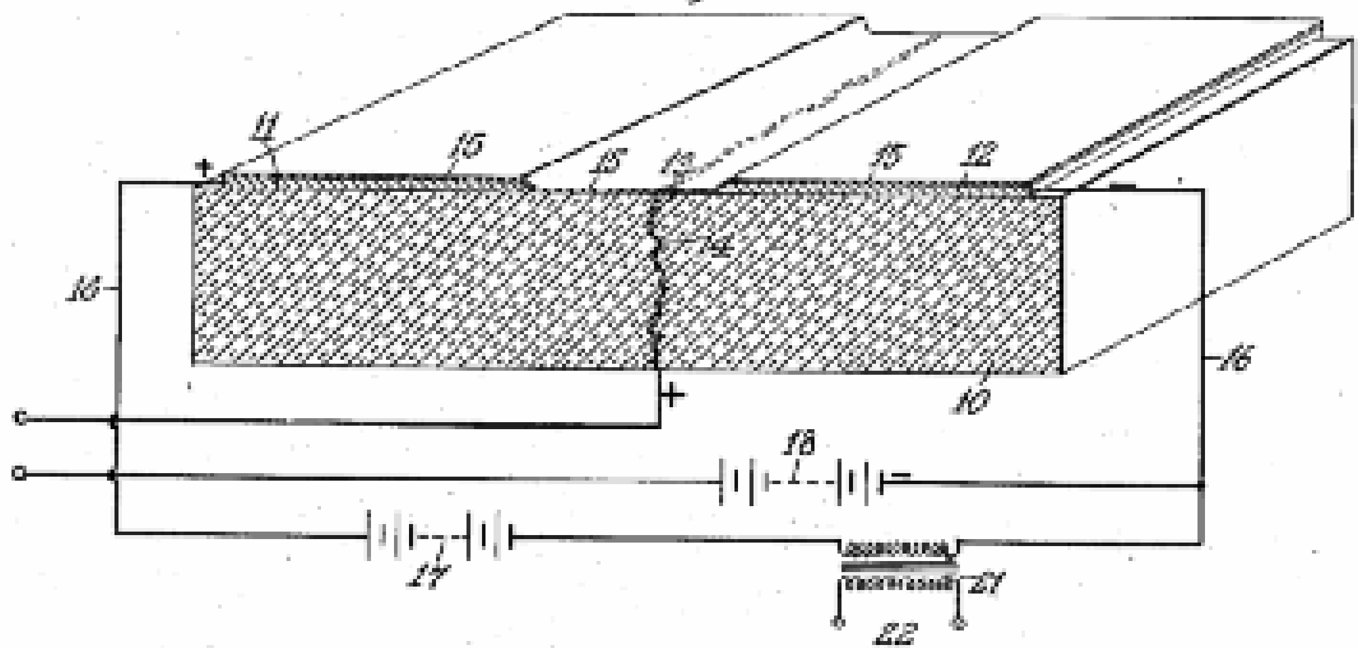
Invention of the Field-Effect Transistor

Jan. 28, 1930. J. E. LILIENFELD 1,745,175

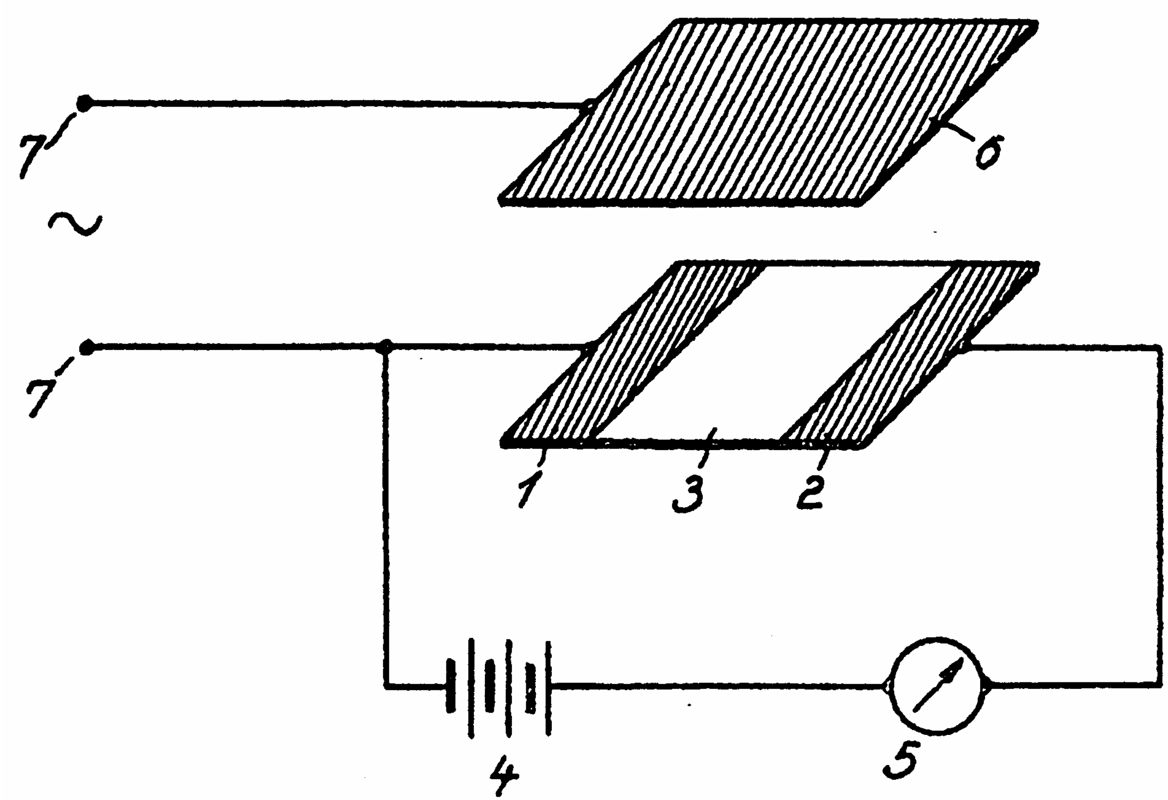
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926

Fig. 1.

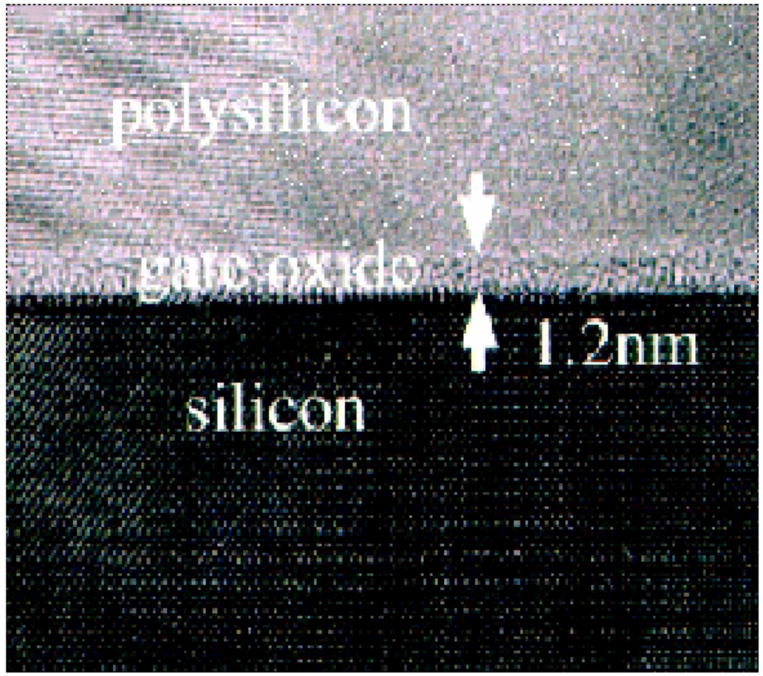


Invention of the Field-Effect Transistor



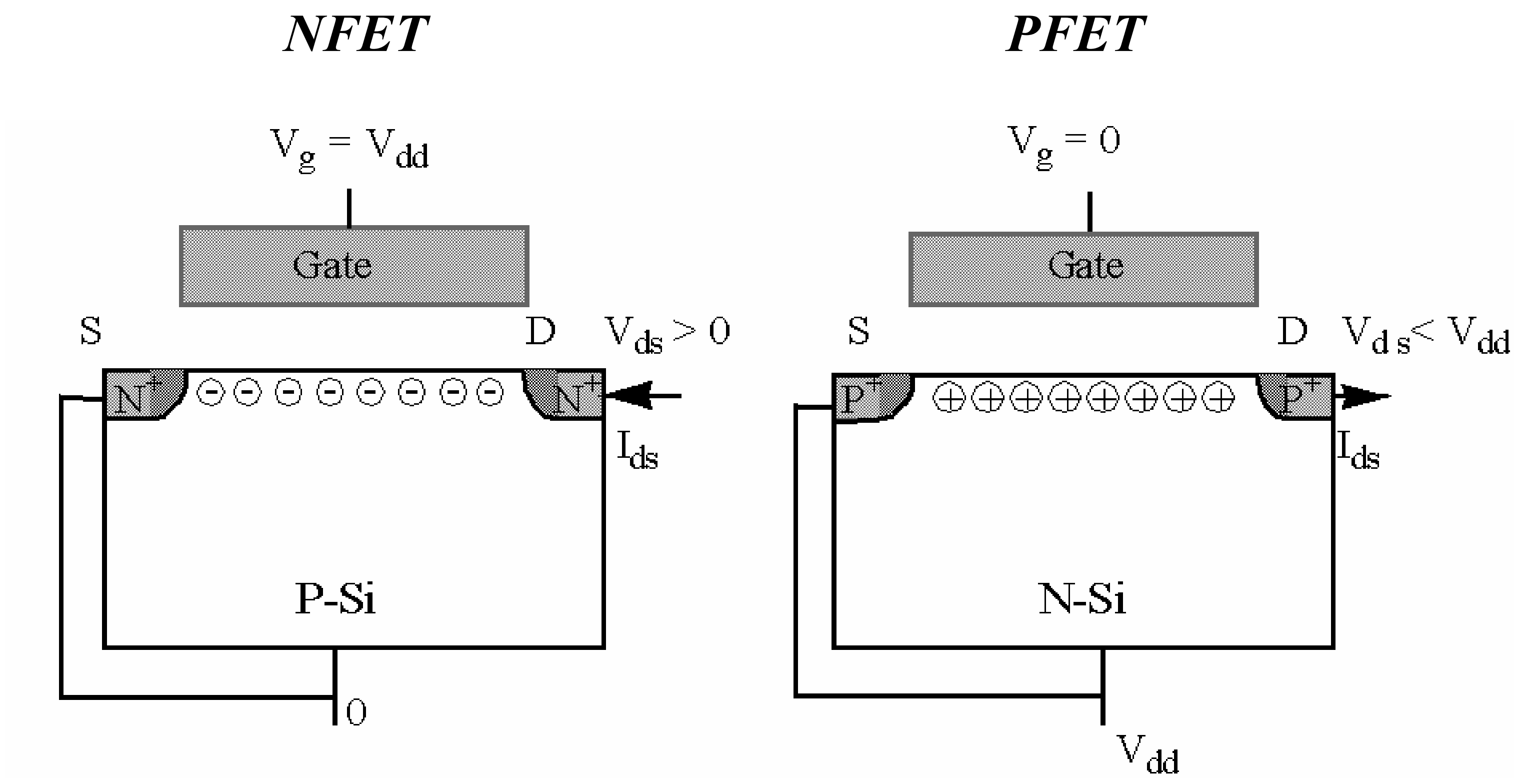
In 1935, a British patent was issued to Oskar Heil.
A working MOSFET was not demonstrated until 1955.
Using today's terminology, what are 1, 2, and 6?

Today's MOSFET Technology



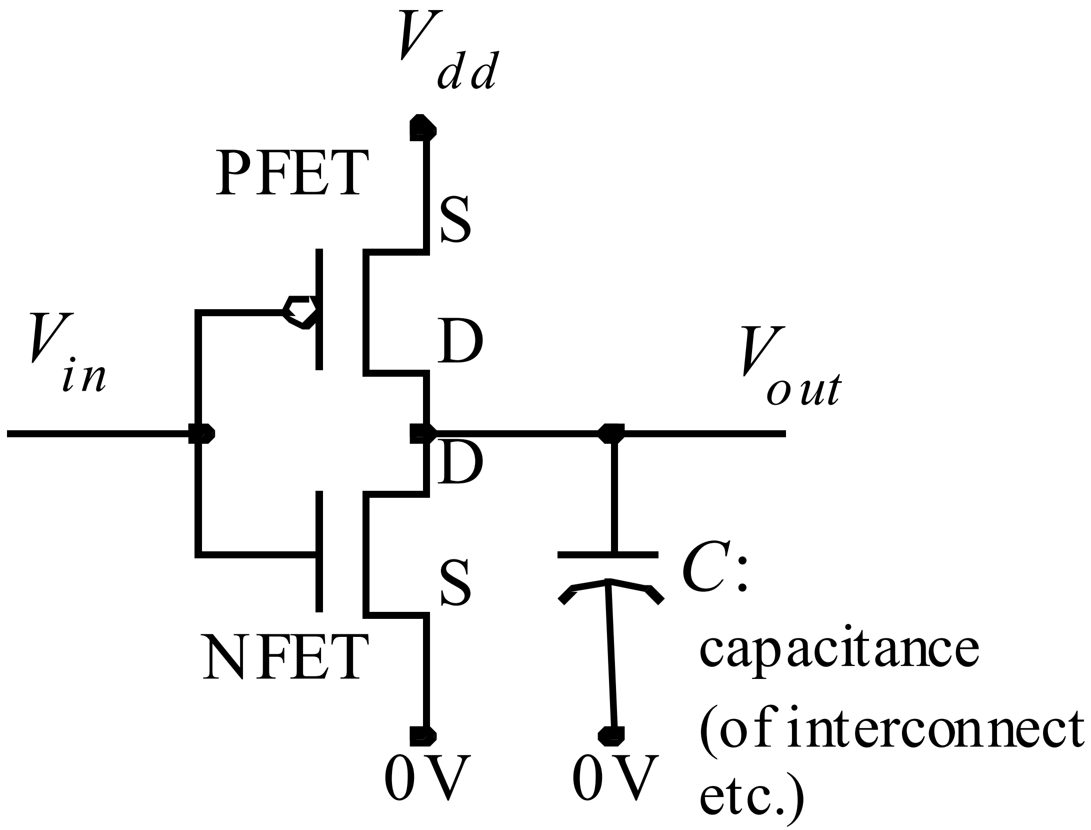
Gate oxides as thin as 1.2 nm can be manufactured reproducibly. Large tunneling current through the oxide limits oxide-thickness reduction.

6.2 Complementary MOSFETs



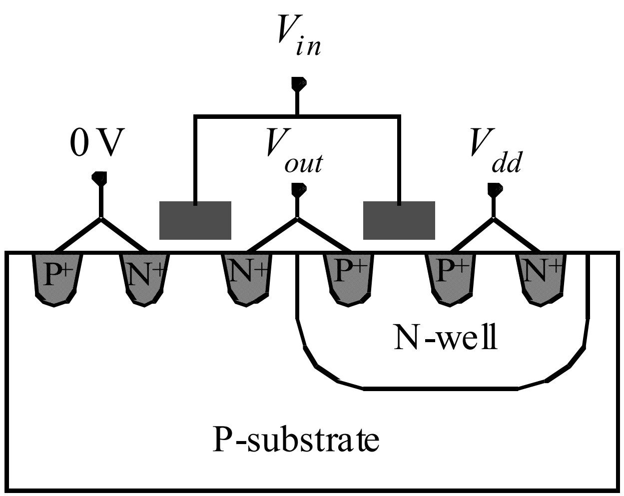
When $V_g = V_{dd}$, the NFET is on and the PFET is off.
When $V_g = 0$, the PFET is on and the NFET is off.

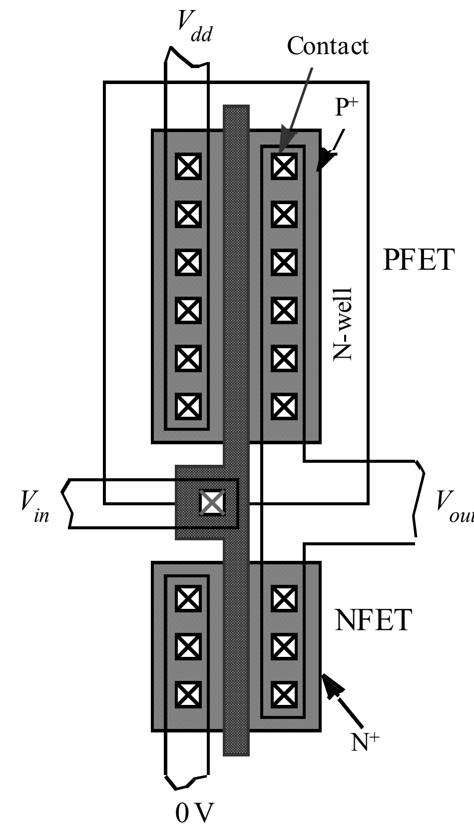
CMOS (Complementary MOS) Inverter



A CMOS inverter is made of a PFET ***pull-up device*** and a NFET ***pull-down device***. V_{out} = ? if V_{in} = 0 V.

CMOS (Complementary MOS) Inverter

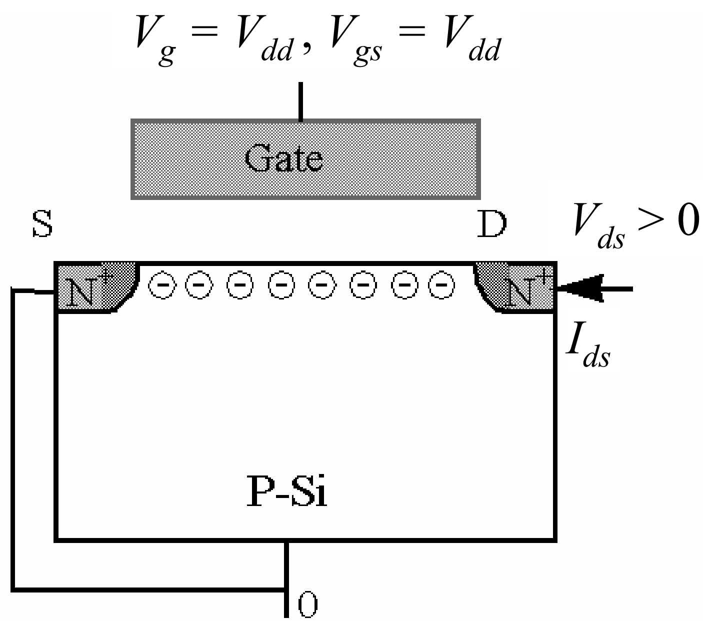




• NFET and PFET can be fabricated on the same chip.

• basic layout of a CMOS inverter

6.3 Surface Mobilities of Electrons and Holes



How to measure the surface mobility:

$$I_{ds} = W \cdot Q_{inv} \cdot v = WQ_{inv}\mu_{ns}\mathcal{E} = WQ_{inv}\mu_{ns}V_{ds} / L$$

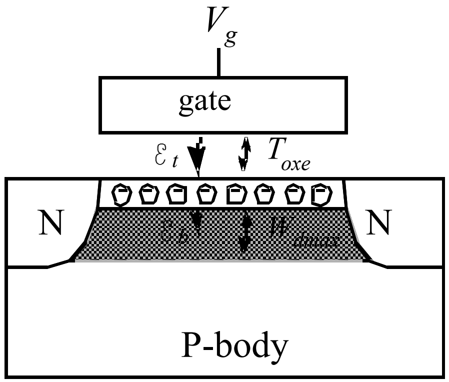
$$= WC_{oxe}(V_g - V_t)\mu_{ns}V_{ds} / L$$

Surface mobility is a function of the average of the fields at the bottom and the top of the inversion charge layer, $\mathcal{E}_b$ and $\mathcal{E}_t$.

From Gauss's Law,

$$\mathcal{E}_b = -Q_{dep}/\varepsilon_s$$

$$V_t = V_{fb} + \phi_{st} - Q_{dep} / C_{oxe}$$



Therefore,

$$\mathcal{E}_b = \frac{C_{oxe}}{\varepsilon_s}(V_t - V_{fb} + \phi_{st})$$

$$\mathcal{E}_t = -(Q_{dep} + Q_{inv}) / \varepsilon_s$$

$$= \mathcal{E}_b - Q_{inv} / \varepsilon_s = \mathcal{E}_b + \frac{C_{oxe}}{\varepsilon_s}(V_{gs} - V_t)$$

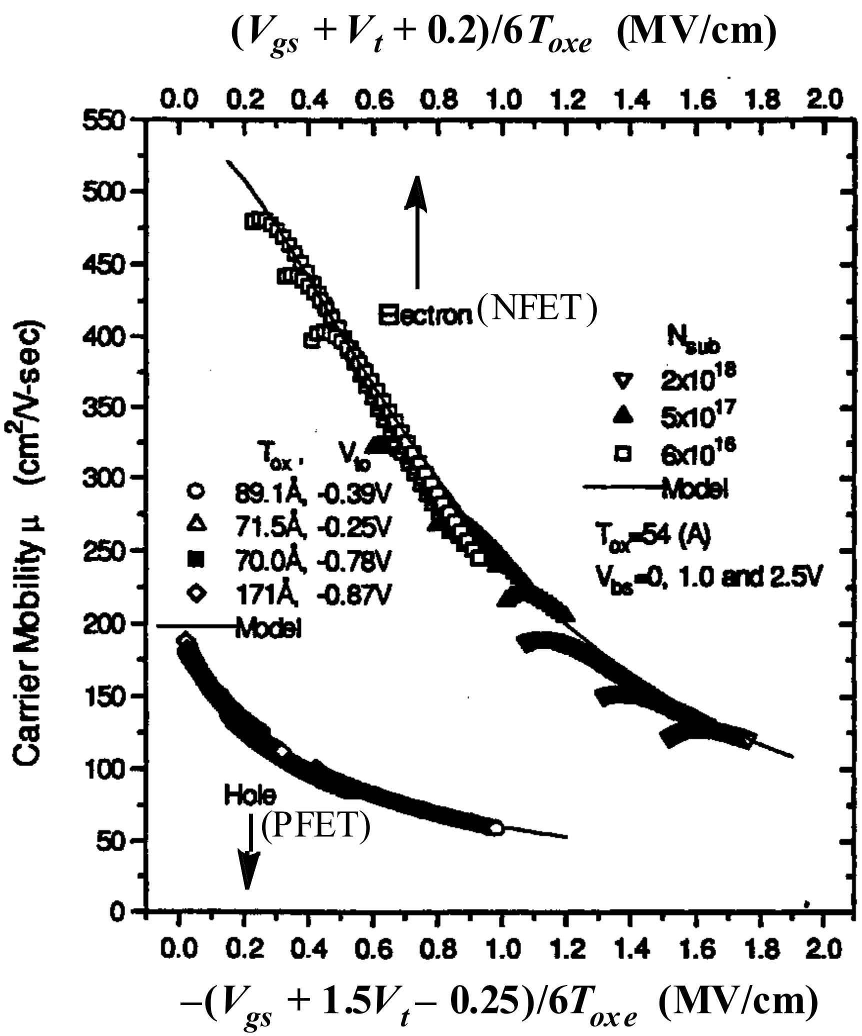
$$= \frac{C_{oxe}}{\varepsilon_s}(V_{gs} - V_{fb} + \phi_{st})$$

$$\therefore \frac{1}{2}(\mathcal{E}_b + \mathcal{E}_t) = \frac{C_{oxe}}{2\varepsilon_s}(V_{gs} + V_t - 2V_{fb} - 2\phi_{st})$$

$$\approx \frac{C_{oxe}}{2\varepsilon_s}(V_{gs} + V_t + 0.2\ \mathrm{V})$$

$$= \frac{V_{gs} + V_t + 0.2\ \mathrm{V}}{6T_{oxe}}$$

Universal Surface Mobilities



Mobility is a function of V_{gs}, V_t, and T_{oxe}.

What suppresses the surface mobility:

- phonon scattering
- coulombic scattering
- surface roughness scattering

EXAMPLE: *What is the surface mobility at V_{gs}=1 V in an N-channel MOSFET with V_t=0.3 V and T_{oxe}=2 nm?*

Solution: $(V_{gs} + V_t + 0.2) / 6T_{oxe}$

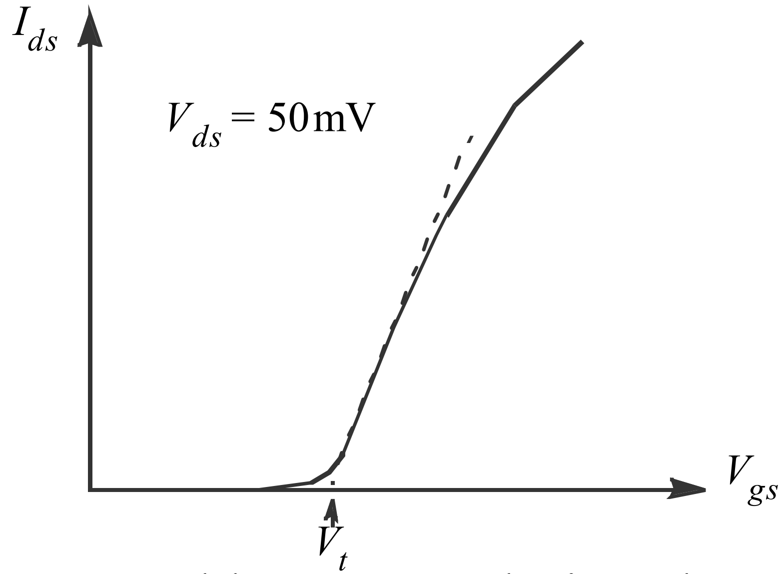
$$= 1.5\,\text{V} / 12 \times 10^{-7}\,\text{cm}$$

$$= 1.25\,\text{MV/cm}$$

1 MV is a megavolt (10^6 V). From the mobility figure, μ_{ns}=190 cm2/Vs, which is several times smaller than the bulk mobility.

6.4 MOSFET V_t and the Body Effect

How to Measure the V_t of a MOSFET

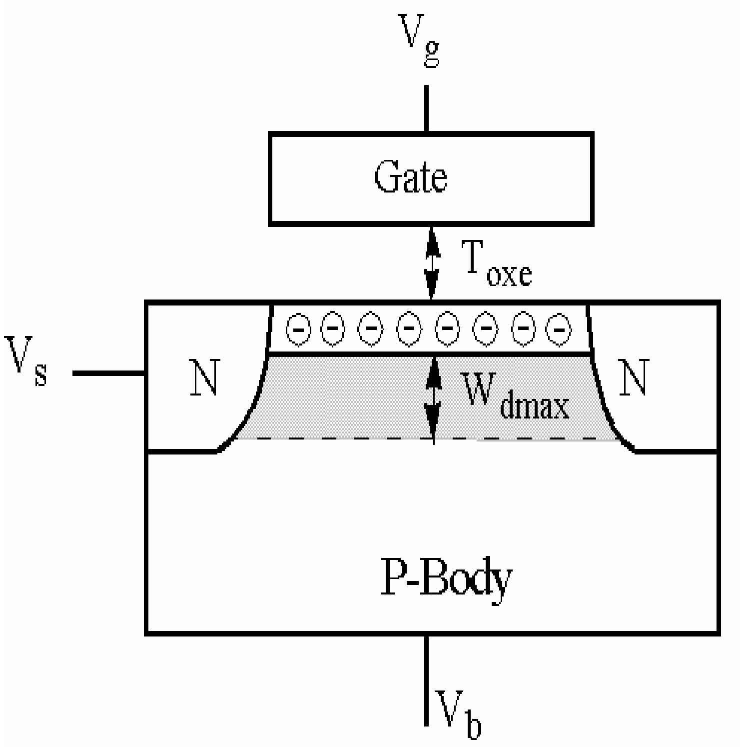


V_t is measured by extrapolating the I_{ds} versus V_{gs} curve to $I_{ds} = 0$.

$$I_{dsat} = \frac{W}{L} C_{oxe} (V_{gs} - V_t) \mu_{ns} V_{ds} \propto V_{gs} - V_t$$

6.4 MOSFET V_t and the Body Effect

$$C_{dep} = \frac{\varepsilon_s}{W_{d\max}}$$



- Two capacitors => two charge components

$$Q_{inv} = -C_{oxe}(V_{gs} - V_t) + C_{dep}V_{sb}$$

$$= -C_{oxe}\left(V_{gs} - \left(V_t + \frac{C_{dep}}{C_{oxe}}V_{sb}\right)\right)$$

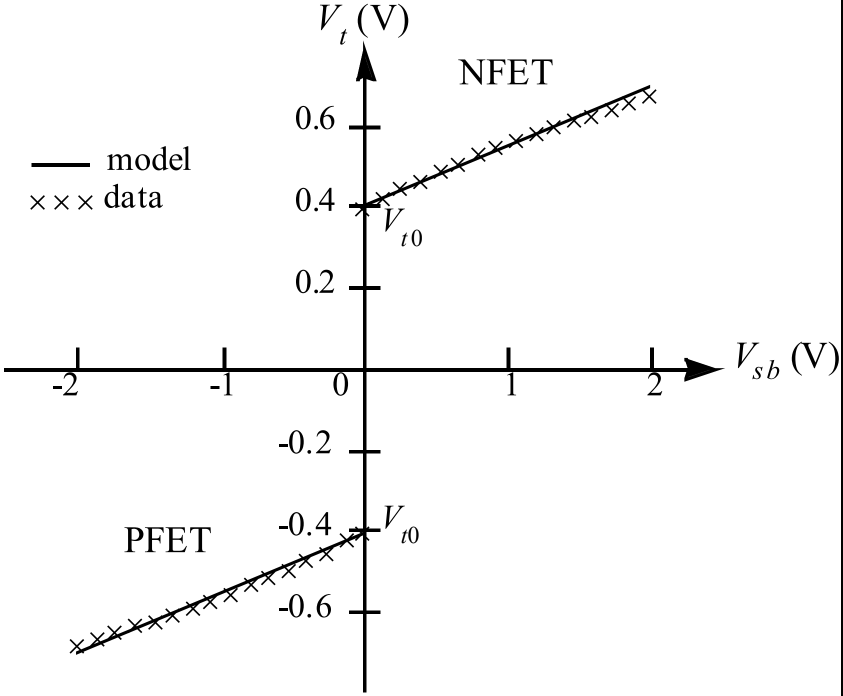
- Redefine V_t as

$$V_t(V_{sb}) = V_{t0} + \frac{C_{dep}}{C_{oxe}}V_{sb} = V_{t0} + \alpha V_{sb}$$

6.4 MOSFET V_t and the Body Effect

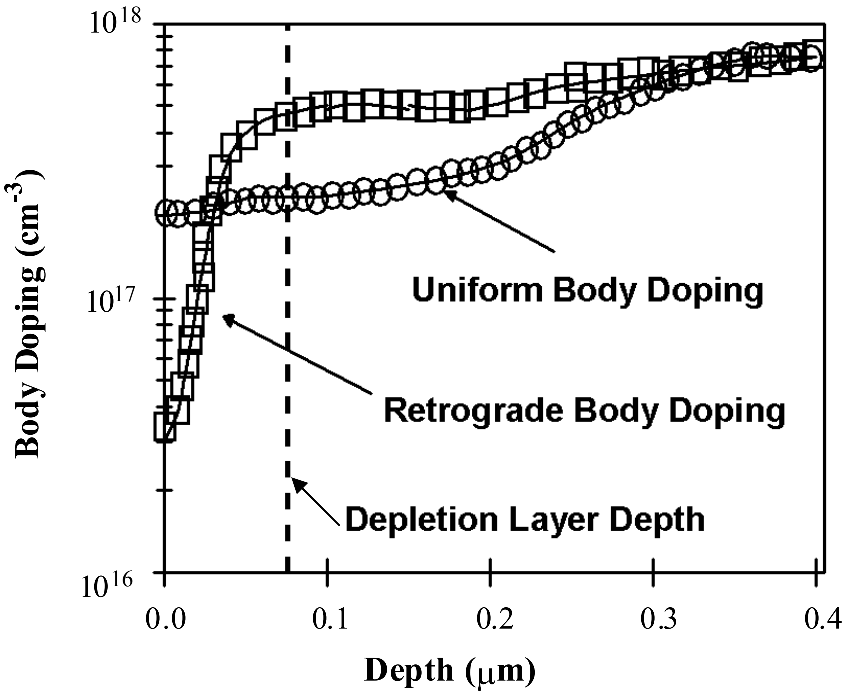
- ***body effect***:
  V_t is a function of V_{sb}
- ***body effect coefficient***:
  $\alpha = C_{dep}/C_{oxe}$
  $= 3T_{oxe} / W_{dmax}$

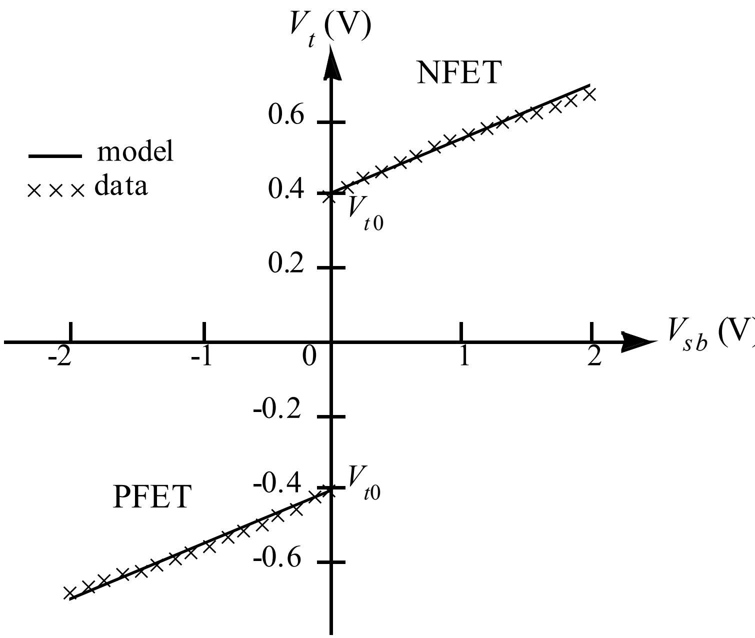
When the source-body junction is reverse-biased, the NFET V_t increases and the PFET V_t becomes more negative.



Is the body effect a good thing? How can it be reduced?

Retrograde Body Doping Profiles





- W_{dep} does not vary with V_{sb} .
- Retrograde doping is popular because it reduces off-state leakage.

Uniform Body Doping

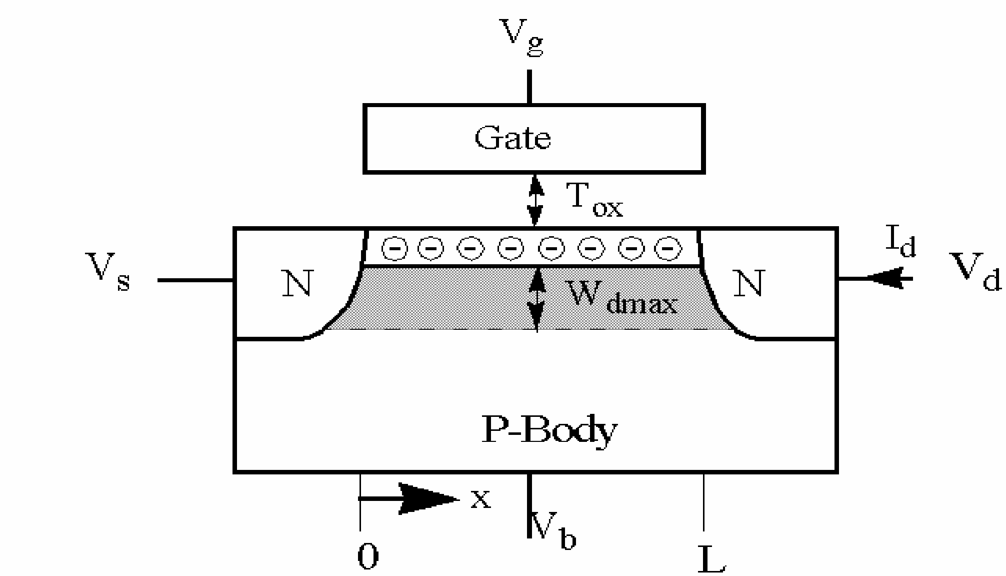
When the source/body junction is reverse-biased, there are two quasi-Fermi levels (E_{fn} and E_{fp}) which are separated by qV_{sb}. An NMOSFET reaches threshold of inversion when E_c is close to E_{fn} , not E_{fp} . This requires the band-bending to be $2\phi_B + V_{sb}$, not $2\phi_B$.

$$V_t = V_{t0} + \frac{\sqrt{qN_a 2\varepsilon_s}}{C_{oxe}}(\sqrt{2\phi_B + V_{sb}} - \sqrt{2\phi_B})$$

$$\equiv V_{t0} + \gamma(\sqrt{2\phi_B + V_{sb}} - \sqrt{2\phi_B})$$

γ is the ***body-effect parameter***.

6.5 Q_{inv} in MOSFET



- Channel voltage $V_c = V_s$ at $x = 0$ and $V_c = V_d$ at $x = L$.

- $$Q_{inv} = -C_{oxe}(V_{gs} - V_{cs} - V_{t0} - \alpha(V_{sb} + V_{cs}))$$
  $$= -C_{oxe}(V_{gs} - V_{cs} - (V_{t0} + \alpha V_{sb}) - \alpha V_{cs})$$
  $$= -C_{oxe}(V_{gs} - mV_{cs} - V_t)$$

- $m \equiv 1 + \alpha = 1 + 3T_{oxe}/W_{dmax}$

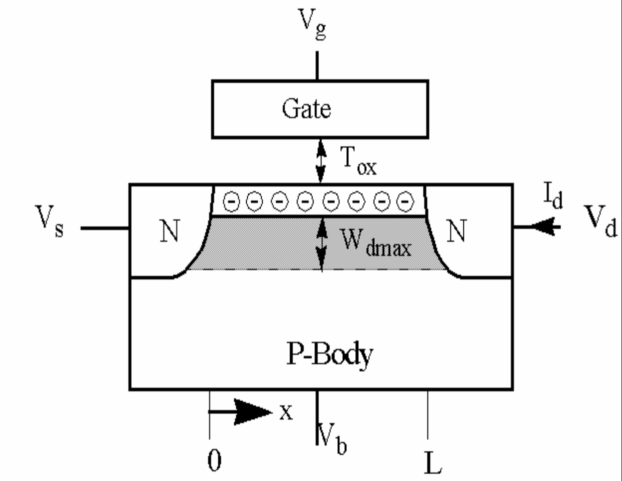
  m is called the ***body-effect factor*** or ***bulk-charge factor***

6.6 Basic MOSFET IV Model

$$I_{ds} = WQ_{inv}v = WQ_{inv}\mu_{ns}\mathcal{E}$$
$$= WC_{oxe}(V_{gs} - mV_{cs} - V_t)\mu_{ns}dV_{cs}/dx$$

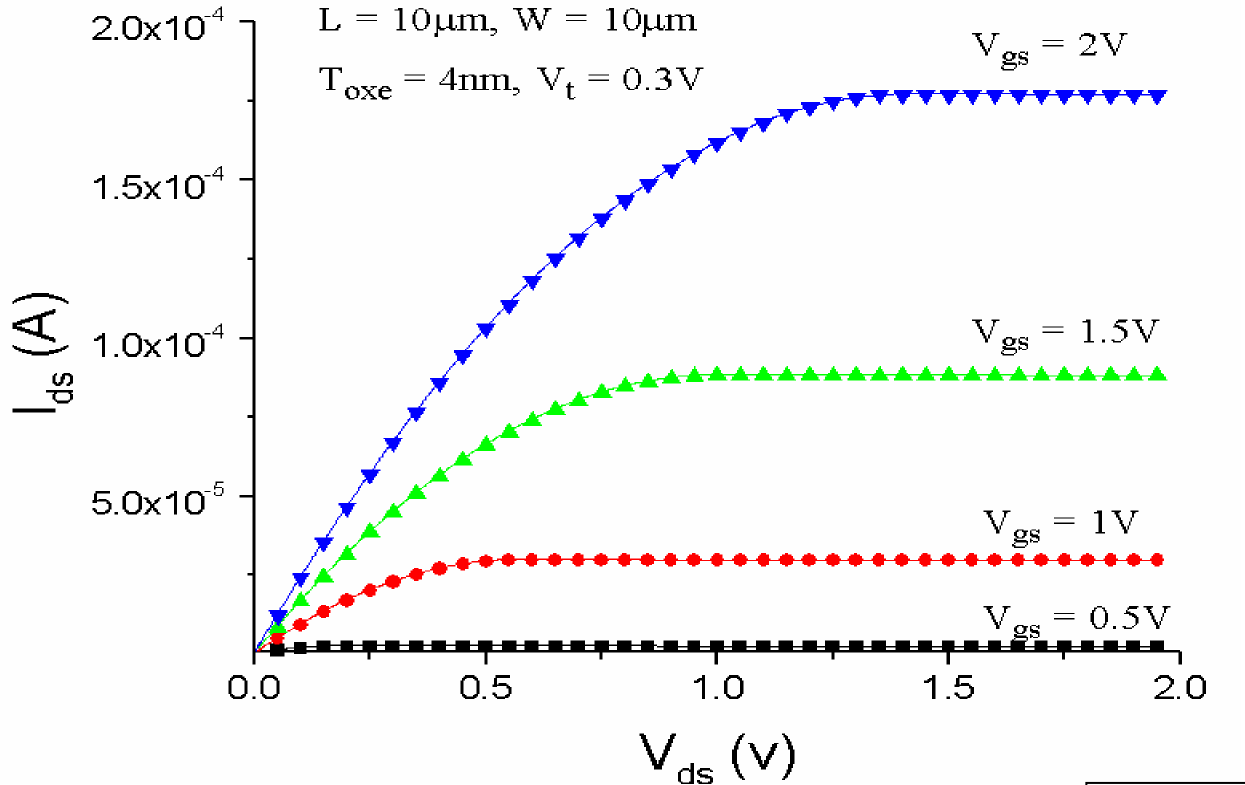
$$\int_0^L I_{ds}dx = WC_{oxe}\mu_{ns}\int_0^{V_{ds}}(V_{gs} - mV_{cs} - V_t)dV_{cs}$$

$$I_{ds}L = WC_{oxe}\mu_{ns}(V_{gs} - V_t - mV_{ds}/2)V_{ds}$$



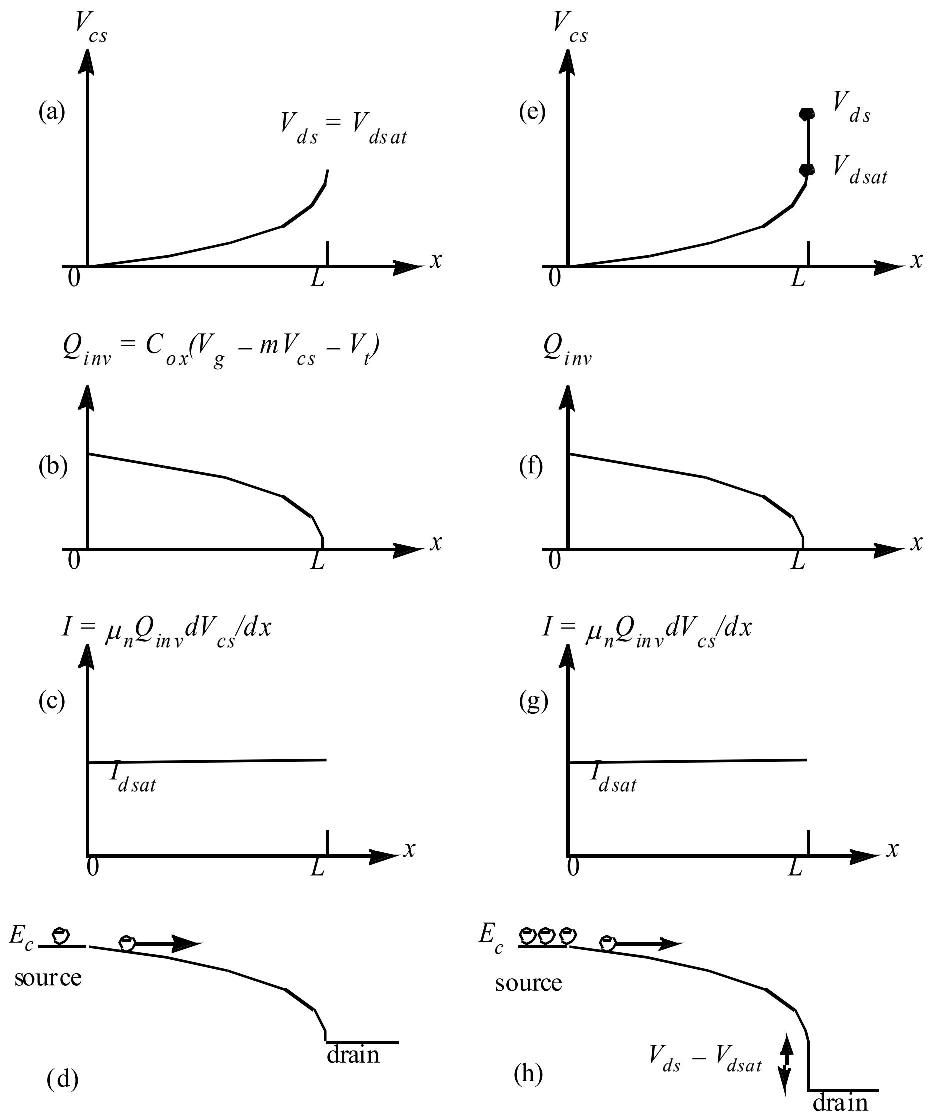
$$I_{ds} = \frac{W}{L}C_{oxe}\mu_s(V_{gs} - V_t - \frac{m}{2}V_{ds})V_{ds}$$

V_{dsat} : Drain Saturation Voltage

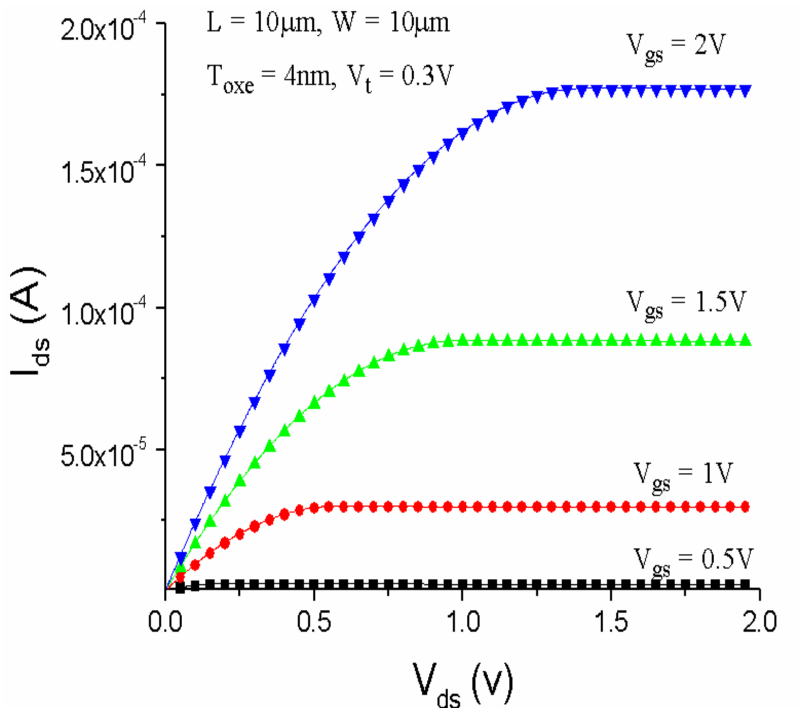


$$\frac{dI_{ds}}{dV_{ds}} = 0 = \frac{W}{L} C_{oxe} \mu_{ns} (V_{gs} - V_t - mV_{ds}) \Rightarrow \boxed{V_{dsat} = \frac{V_{gs} - V_t}{m}}$$

$V_{ds} = V_{dsat}$ $\qquad$ $V_{ds} > V_{dsat}$



Saturation Current and Transconductance



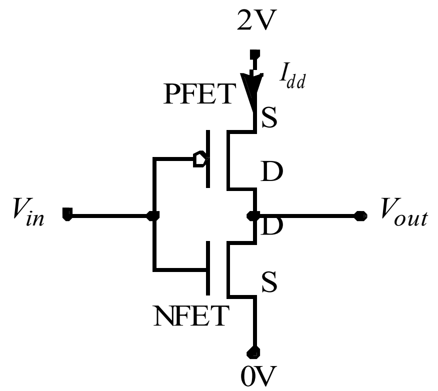
- linear region, saturation region

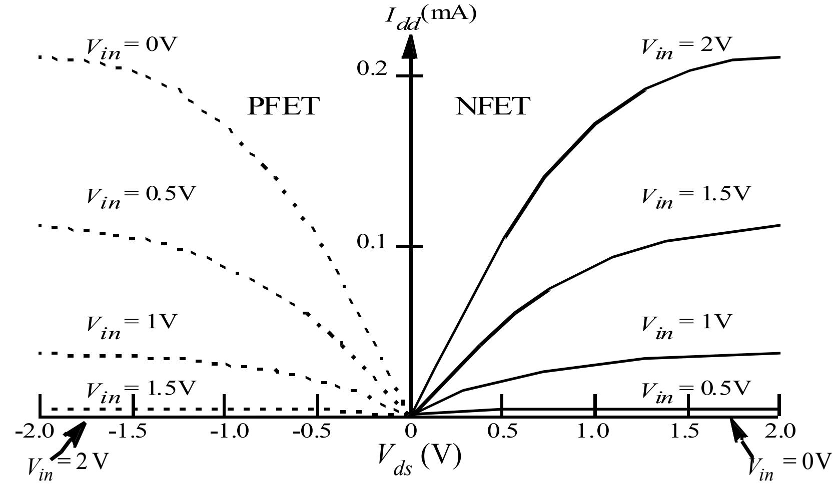
$$I_{dsat} = \frac{W}{2mL} C_{oxe} \mu_{ns} (V_{gs} - V_t)^2$$

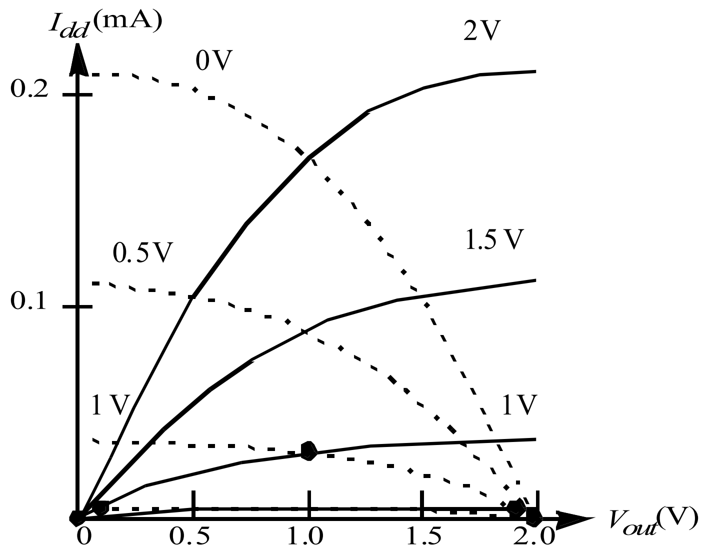
- transconductance: $g_m = dI_{ds}/dV_{gs}$

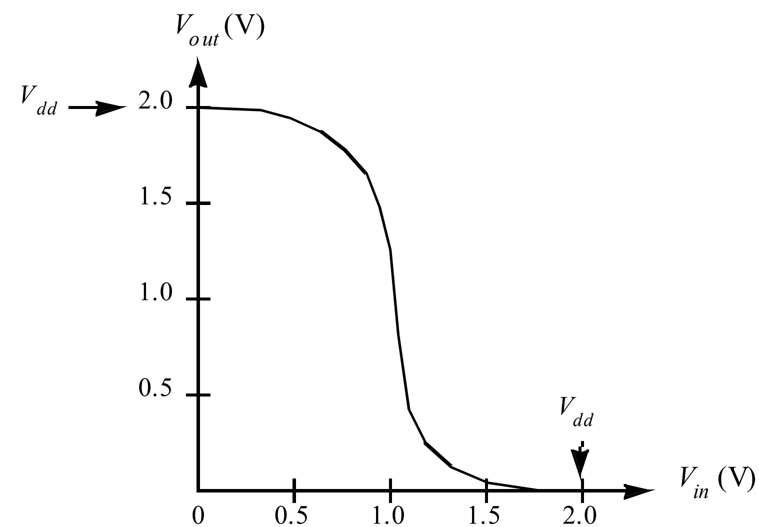
$$g_{msat} = \frac{W}{mL} C_{oxe} \mu_{ns} (V_{gs} - V_t)$$

6.7.1 CMOS Inverter Voltage Transfer Curve – Regeneration of Digital Signal

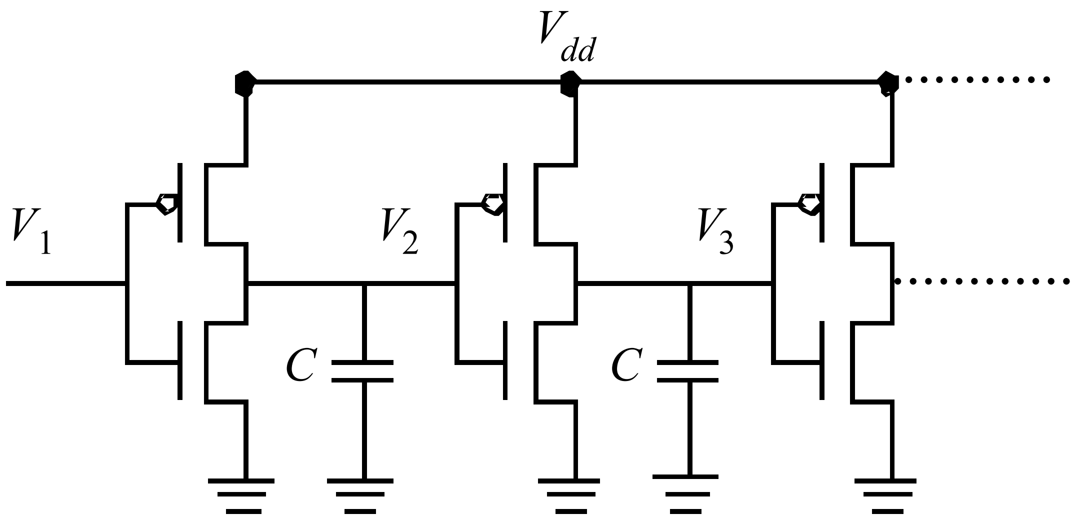


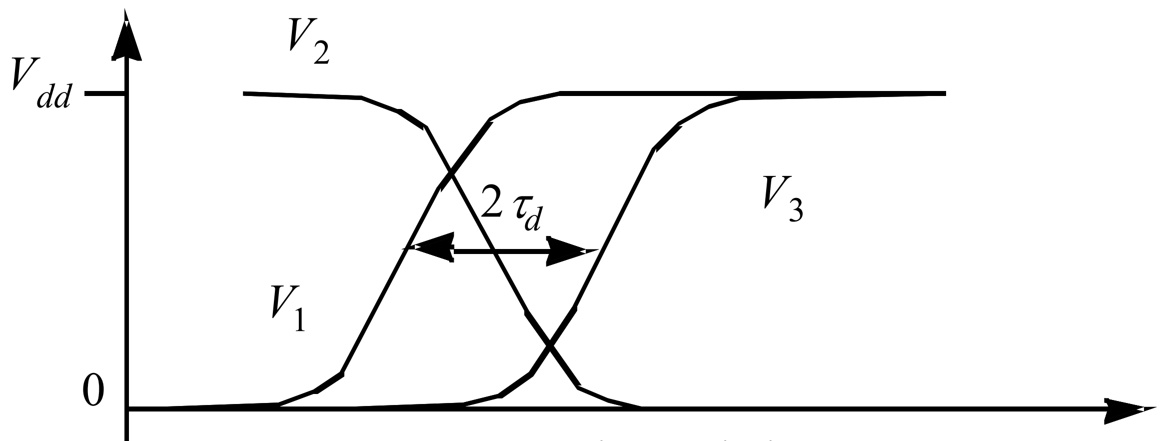






6.7.2 CMOS Inverter Delay





τ_d : propagation delay

6.7.2 CMOS Inverter Delay

$$\tau_d \equiv \frac{1}{2}(pull-down\ delay\ +\ pull-up\ delay)$$

$$pull-up\ delay \approx \frac{CV_{dd}}{2I_{dsatP}}$$

$$pull-down\ delay \approx \frac{CV_{dd}}{2I_{dsatN}}$$

$$\tau_d = \frac{CV_{dd}}{4}\left(\frac{1}{I_{dsatN}} + \frac{1}{I_{dsatP}}\right)$$

$$R_N \text{ and } R_P = \frac{V_{dd}}{2I_{on}} = \frac{V_{dd}}{2I_{dsat}(|V_g| = V_{dd})}$$

How can the speed of an inverter circuit be improved?

6.7.3 CMOS Power Consumption

$$P_{dynamic} = V_{dd} \times average\ current = CV_{dd}^2 f$$

$$P_{static} = V_{dd} I_{off}$$

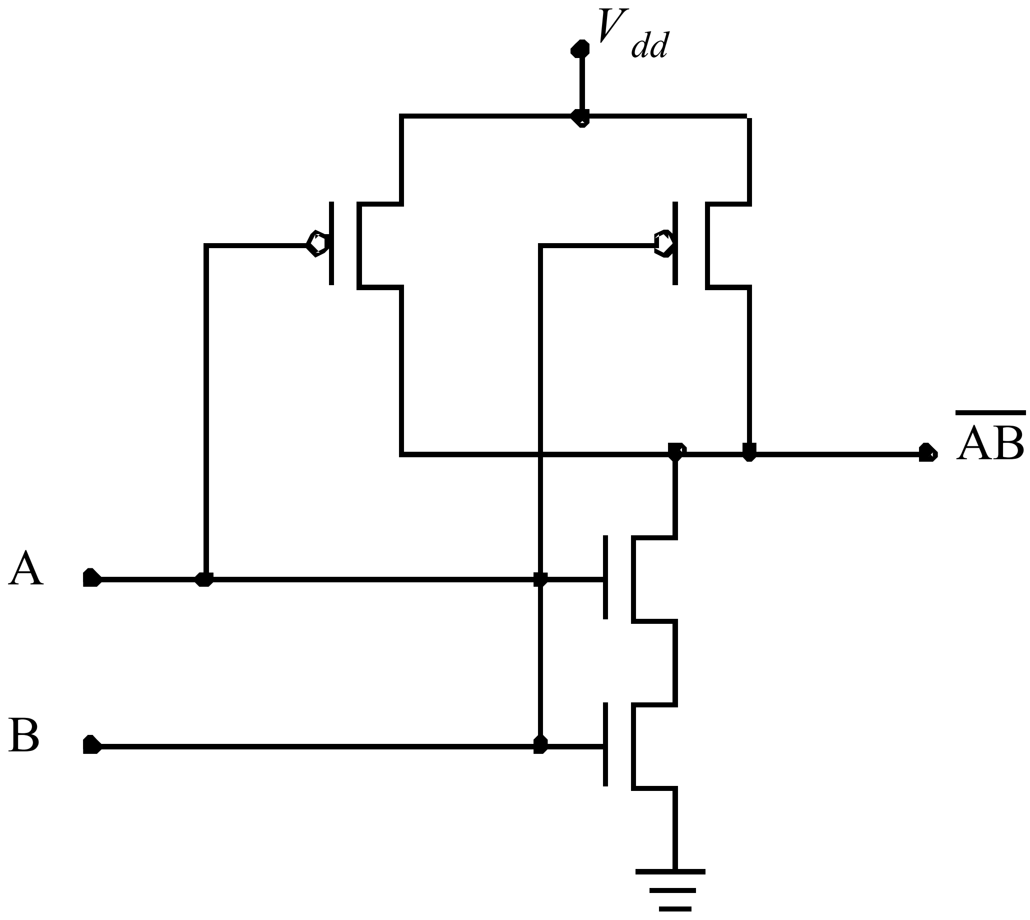
$$P_{direct-path} \approx V_{dd} \frac{I_{dsat}}{5} \frac{t_r + t_f}{2} f = 0.2 CV_{dd}^2 f$$

$$= 0.2 P_{dynamic}$$

Total power consumption

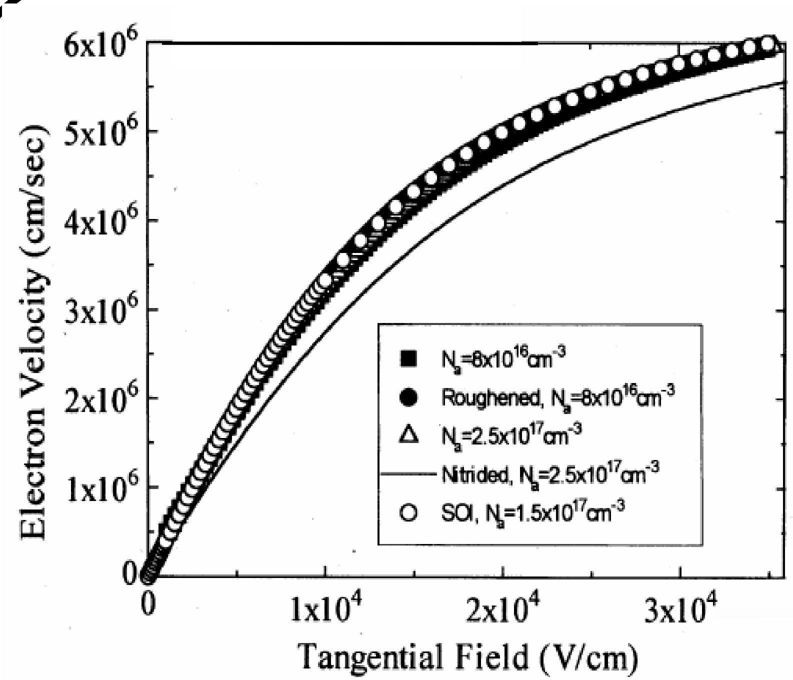
$$P = 1.2 CV_{dd}^2 f + V_{dd} I_{off}$$

Logic Gates



This two-input NAND gate and many other logic gates are extensions of the inverter.

6.8 Velocity Saturation

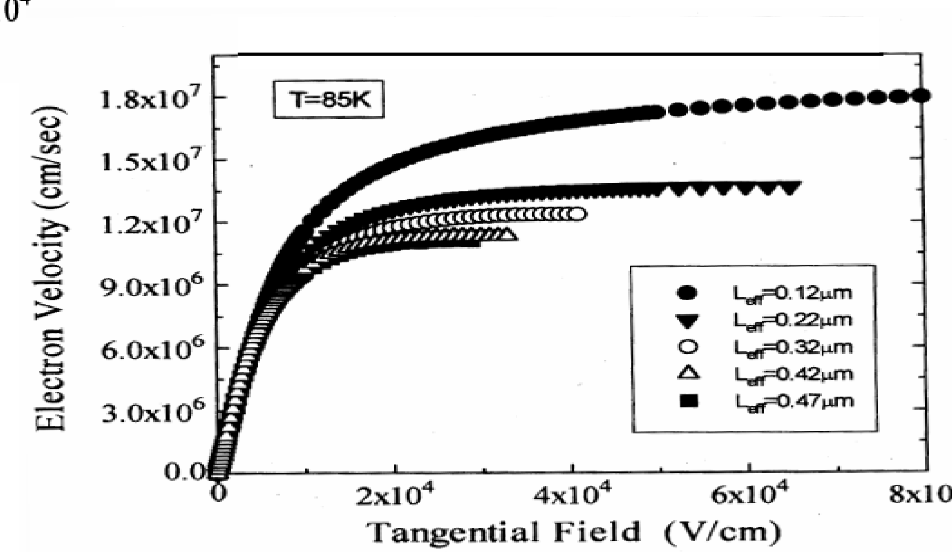


$$v = \frac{\mu_s \mathcal{E}}{1 + \dfrac{\mathcal{E}}{\mathcal{E}_{sat}}}$$

$$\mathcal{E} << \mathcal{E}_{sat} : v = \mu_s \mathcal{E}$$

$$\mathcal{E} >> \mathcal{E}_{sat} : v = \mu_s \mathcal{E}_{sat}$$

• velocity saturation has large and deleterious effect on the I_{on} of MOSFETS



6.9 MOSFET IV Model with Velocity Saturation

$$I_{ds} = WQ_{inv}v$$

$$I_{ds} = WC_{oxe}(V_{gs} - mV_{cs} - V_t)\frac{\mu_{ns} dV_{cs}/dx}{1 + \dfrac{dV_{cs}}{dx}/\mathcal{E}_{sat}}$$

$$\int_0^L I_{ds}dx = \int_0^{V_{ds}} [WC_{oxe}\mu_{ns}(V_{gs} - mV_{cs} - V_t) - I_{ds}/\mathcal{E}_{sat}]dV_{cs}$$

$$I_{ds}L = WC_{oxe}\mu_{ns}(V_{gs} - V_t - \frac{m}{2}V_{ds})V_{ds} - I_{ds}V_{ds}/\mathcal{E}_{sat}$$

6.9 MOSFET IV Model with Velocity Saturation

$$I_{ds} = \frac{\frac{W}{L} C_{oxe} \mu_{ns} (V_{gs} - V_t - \frac{m}{2} V_{ds}) V_{ds}}{1 + \frac{V_{ds}}{\mathcal{E}_{sat} L}}$$

$$\boxed{I_{ds} = \frac{long\text{-}channel\ I_{ds}}{1 + V_{ds} / \mathcal{E}_{sat} L}}$$

6.9 MOSFET IV Model with Velocity Saturation

Solving $\frac{dI_{ds}}{dV_{ds}} = 0,$

$$V_{dsat} = \frac{2(V_{gs} - V_t)/m}{1 + \sqrt{1 + 2(V_{gs} - V_t)/m\mathcal{E}_{sat}L}}$$

A simpler and more accurate V_{dsat} is:

$$\boxed{\frac{1}{V_{dsat}} = \frac{m}{V_{gs} - V_t} + \frac{1}{\mathcal{E}_{sat}L}}$$

$$\mathcal{E}_{sat} \equiv \frac{2v_{sat}}{\mu_s}$$

EXAMPLE: Drain Saturation Voltage

Question: *At V_{gs} = 1.8 V, what is the V_{dsat} of an NFET with T_{oxe} = 3 nm, V_t = 0.25 V, and W_{dmax} = 45 nm for (a) L =10 μm, (b) L = 1 um, (c) L = 0.1 μm, and (d) L = 0.05 μm?*

Solution: *From V_{gs}, V_t, and T_{oxe}, μ_{ns} is 200 $cm^2V^{-1}s^{-1}$.*

$$\mathcal{E}_{sat} = 2v_{sat}/\mu_{es} = 8 \times 10^4 \text{ V/cm}$$

$$m = 1 + 3T_{oxe}/W_{dmax} = 1.2$$

$$V_{dsat} = \left(\frac{m}{V_{gs} - V_t} + \frac{1}{\mathcal{E}_{sat} L} \right)^{-1}$$

EXAMPLE: Drain Saturation Voltage

$$V_{dsat} = \left(\frac{m}{V_{gs} - V_t} + \frac{1}{\mathcal{E}_{sat} L} \right)^{-1}$$

(a) L = 10 μm, V_{dsat} = $(1/1.3\text{V} + 1/80\text{V})^{-1}$ = 1.3 V

(b) L = 1 μm, V_{dsat} = $(1/1.3\text{V} + 1/8\text{V})^{-1}$ = 1.1 V

(c) L = 0.1 μm, V_{dsat} = $(1/1.3\text{V} + 1/.8\text{V})^{-1}$ = 0.5 V

(d) L = 0.05 μm, V_{dsat} = $(1/1.3\text{V} + 1/.4\text{V})^{-1}$ = 0.3 V

I_{dsat} with Velocity Saturation

Substituting V_{dsat} for V_{ds} in I_{ds} equation gives:

$$I_{dsat} = \frac{W}{2mL} C_{oxe} \mu_s \frac{(V_{gs} - V_t)^2}{1 + \dfrac{V_{gs} - V_t}{m\mathcal{E}_{sat} L}} = \frac{long\text{-}channel\ I_{dsat}}{1 + \dfrac{V_{gs} - V_t}{m\mathcal{E}_{sat} L}}$$

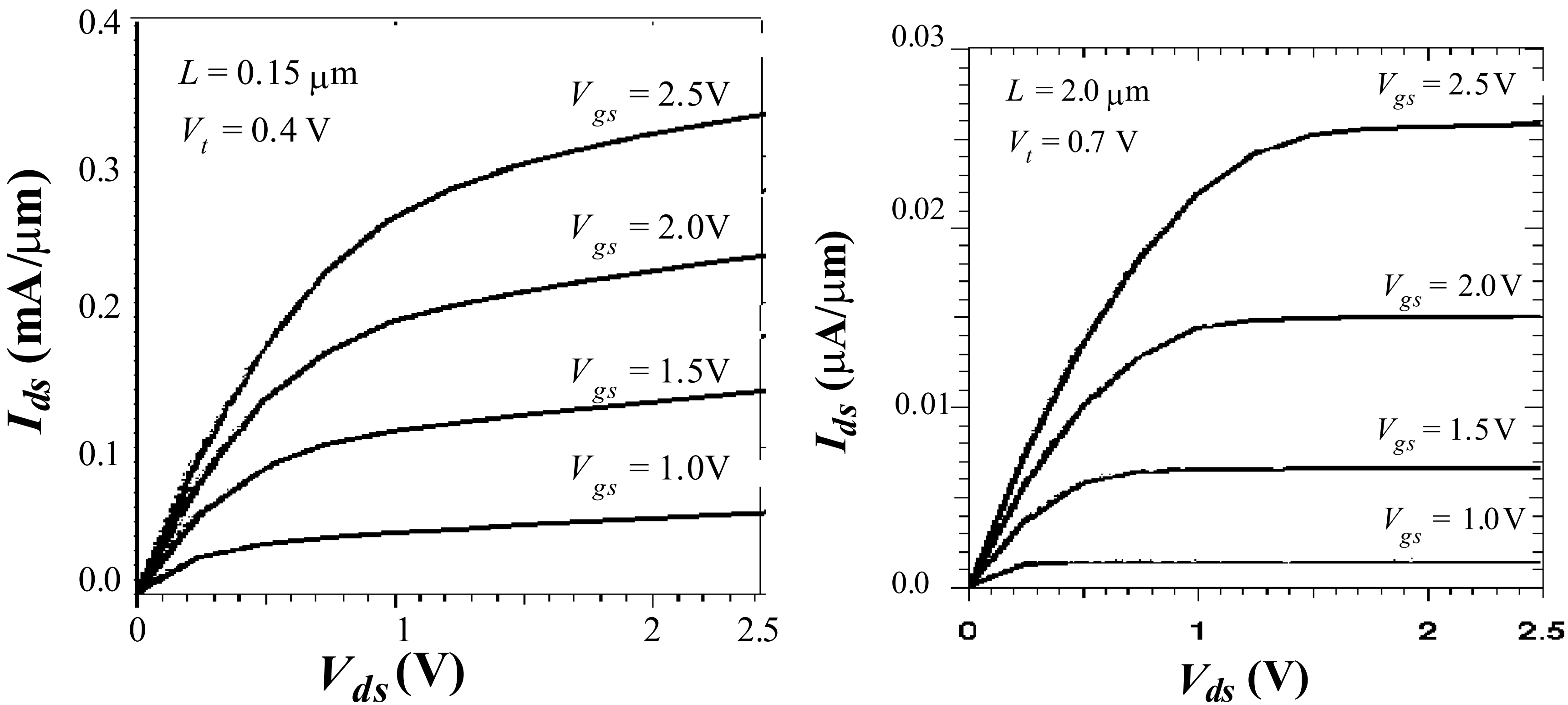
Very short channel case: $\mathcal{E}_{sat} L << V_{gs} - V_t$

$$I_{dsat} = \frac{W}{2} C_{oxe} \mu_s \mathcal{E}_{sat} (V_{gs} - V_t)$$

$$= W v_{sat} C_{oxe} (V_{gs} - V_t - \mathcal{E}_{sat} L)$$

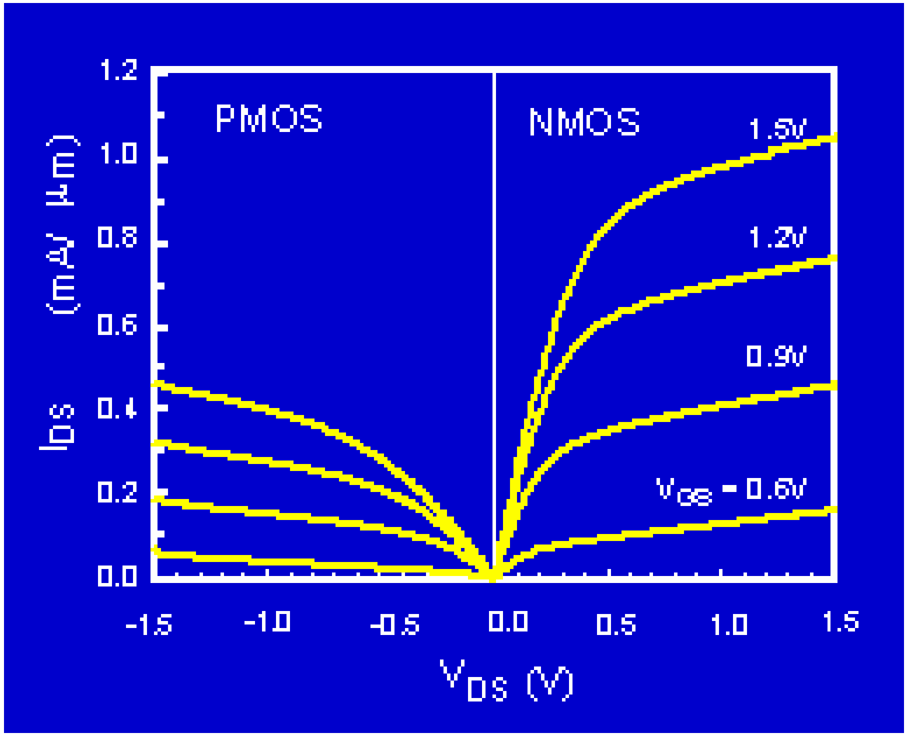
- I_{dsat} is proportional to $V_{gs} - V_t$ rather than $(V_{gs} - V_t)^2$, not as sensitive to L as $1/L$.

Measured MOSFET IV



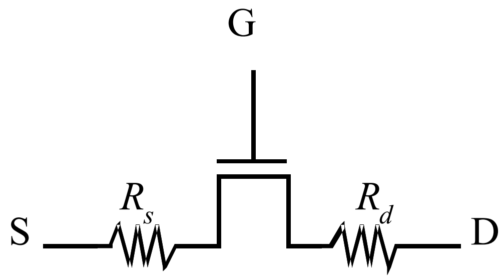
What is the main difference between the V_g dependences of the long- and short-channel length IV curves?

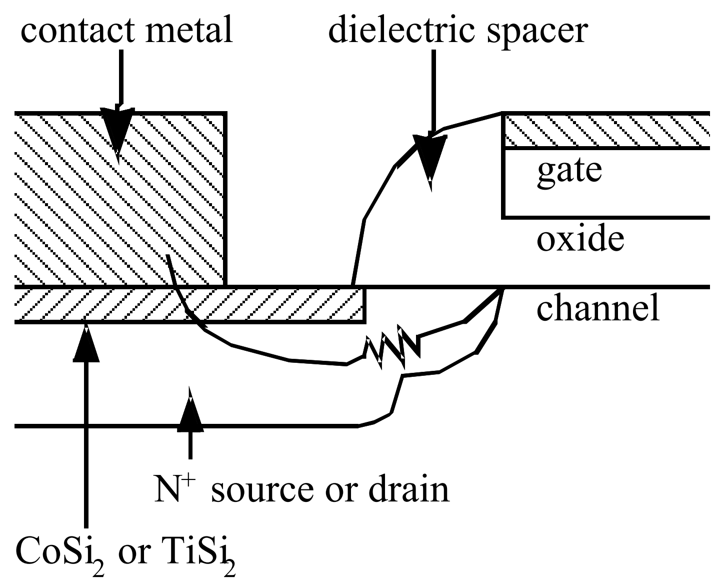
PMOS and NMOS IV Characteristics



The PMOS IV is qualitatively similar to the NMOS IV, but the current is about half as large. How can we design a CMOS inverter so that its voltage transfer curve is symmetric?

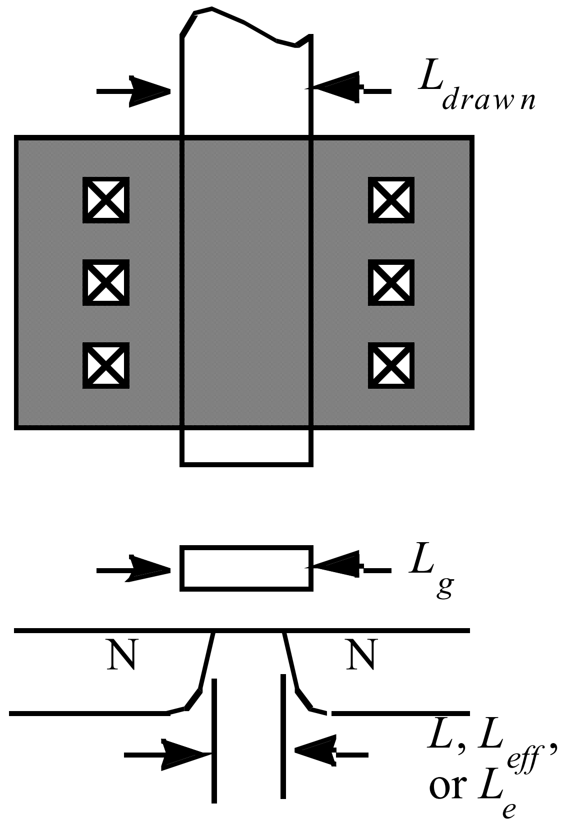
6.10 Parasitic Source-Drain Resistance





- If $I_{dsat0} \propto V_g - V_t$, $I_{dsat} = \dfrac{I_{dsat0}}{1 + \dfrac{I_{dsat0} R_s}{(V_{gs} - V_t)}}$
- I_{dsat} is reduced by about 15% in a 0.1μm MOSFET.
- $V_{dsat} = V_{dsat0} + I_{dsat}(R_s + R_d)$

Definitions of Channel Length



$$L \equiv L_{drawn} - \Delta L$$

6.11 Extraction of the Series Resistance and the Effective Channel Length

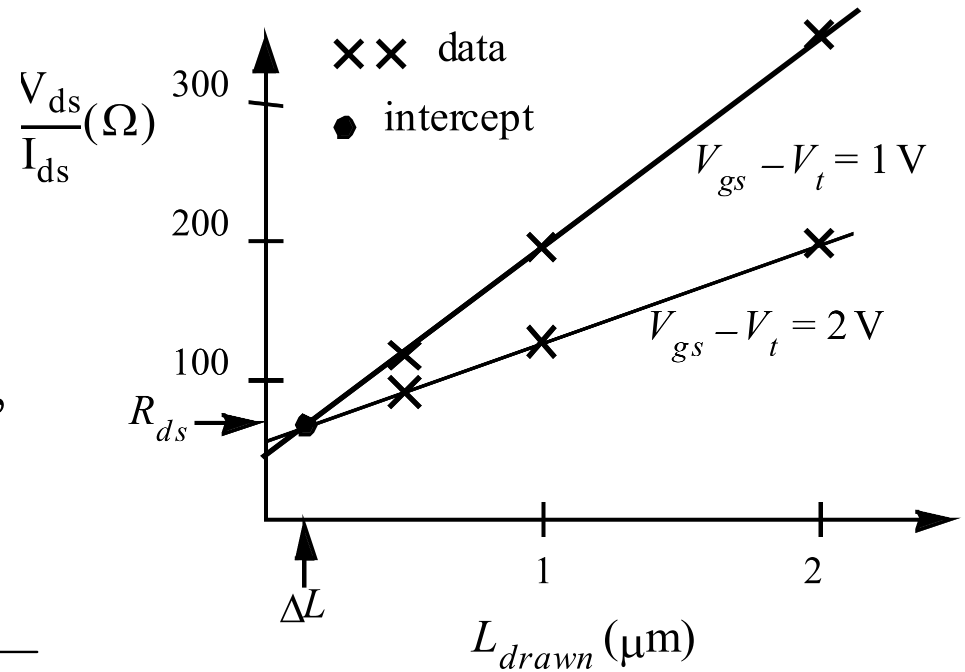
$$I_{ds} = \frac{WC_{oxe}\mu_s V_{ds}}{L_{drawn} - \Delta L}(V_{gs} - V_t)$$

$$V_{ds} = \frac{I_{ds}(L_{drawn} - \Delta L)}{WC_{oxe}(V_{gs} - V_t)\mu_s}$$

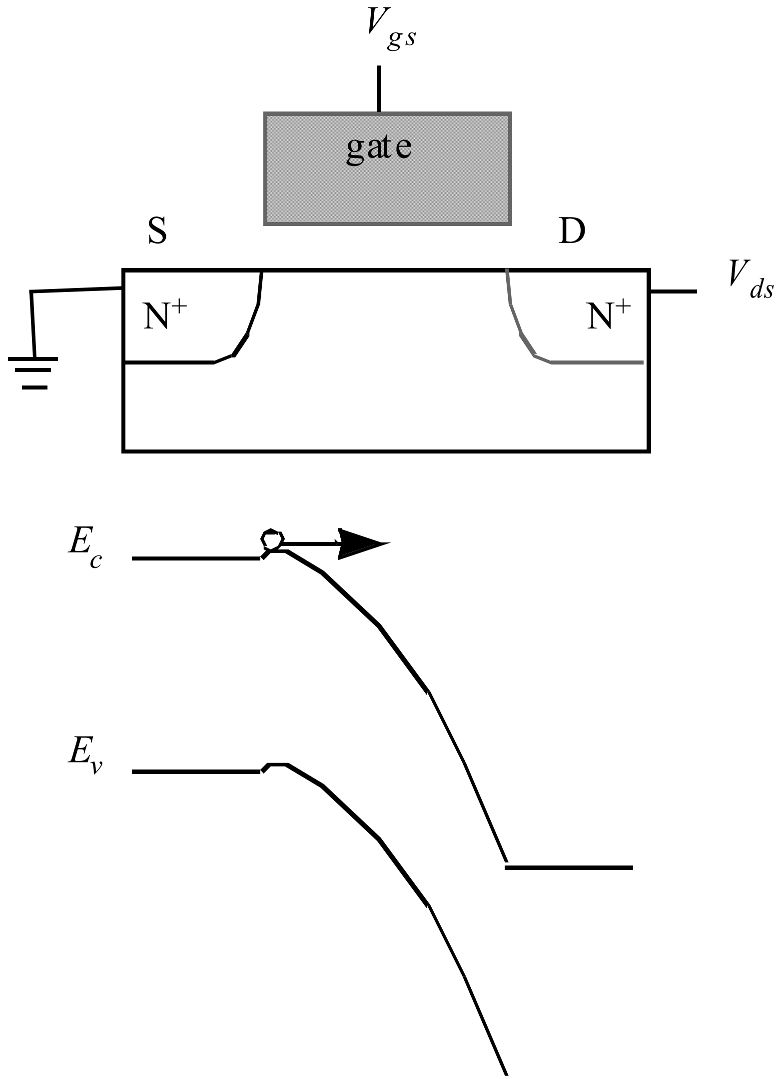
Include series resistance,

$R_{ds} \equiv R_d + R_s$,

$$\frac{V_{ds}}{I_{ds}} = R_{ds} + \frac{L_{drawn} - \Delta L}{WC_{oxe}(V_{gs} - V_t)\mu_s}$$



6.12 Source Injection Velocity Limit



- Carrier velocity is limited by the thermal velocity when they first enter the channel from the source.

- $$I_{dsat} = WBv_{thx}Q_{inv}$$
  $$= WBv_{thx}C_{oxe}(V_{gs} - V_t)$$

6.13 Chapter Summary

- ***body effect***

$$V_t(V_{sb}) = V_{t0} + \alpha V_{sb}$$ for steep retrograde body doping

$$\alpha = 3T_{oxe} / W_{dmax}$$

- ***basic I_{ds} model***

$$I_{ds} = \frac{W}{L} C_{oxe} \mu_s (V_{gs} - V_t - \frac{m}{2} V_{ds}) V_{ds}$$

$$m = 1 + 3T_{oxe} / W_{dmax} \approx 1.2$$

- Small α and m are desirable. Therefore, small T_{oxe} is good. Ch.7 shows that large W_{dmax} is not acceptable.
- CMOS circuit speed is determined by CV_{dd}/I_{dsat}, and its power by $CV_{dd}^2 f + V_{dd} I_{off}$.

6.13 Chapter Summary

IV characteristics can be divided into a ***linear region*** and a ***saturation region.***

I_{ds} saturates at:

$$V_{dsat} = \frac{V_{gs} - V_t}{m}$$

$$I_{dsat} = \frac{W}{2mL} C_{oxe} \mu_s (V_{gs} - V_t)^2$$

transconductance:

$$g_{msat} = \frac{W}{mL} C_{oxe} \mu_s (V_{gs} - V_t)$$

Considering ***velocity saturation,***

$$V_{dsat} = \left(\frac{m}{V_{gs} - V_t} + \frac{1}{\mathcal{E}_{sat} L} \right)^{-1}$$

$$I_{dsat} = \frac{\text{long-channel } I_{dsat}}{1 + \frac{V_{gs} - V_t}{m \mathcal{E}_{sat} L}}$$