Chapter 17-1. MOSFET

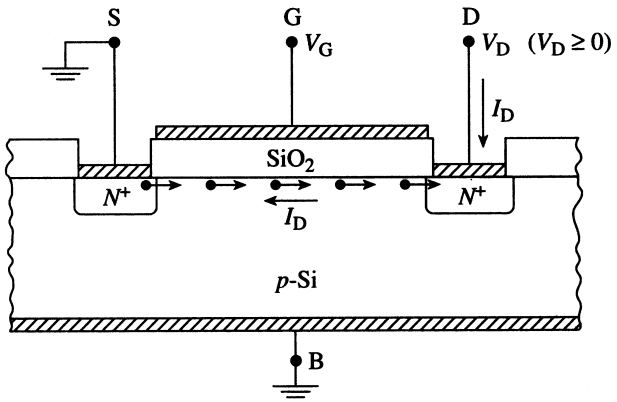
MOSFET based ICs have become dominant technology in the semiconductor industry.

We will study the following in this chapter:

Qualitative theory of operation

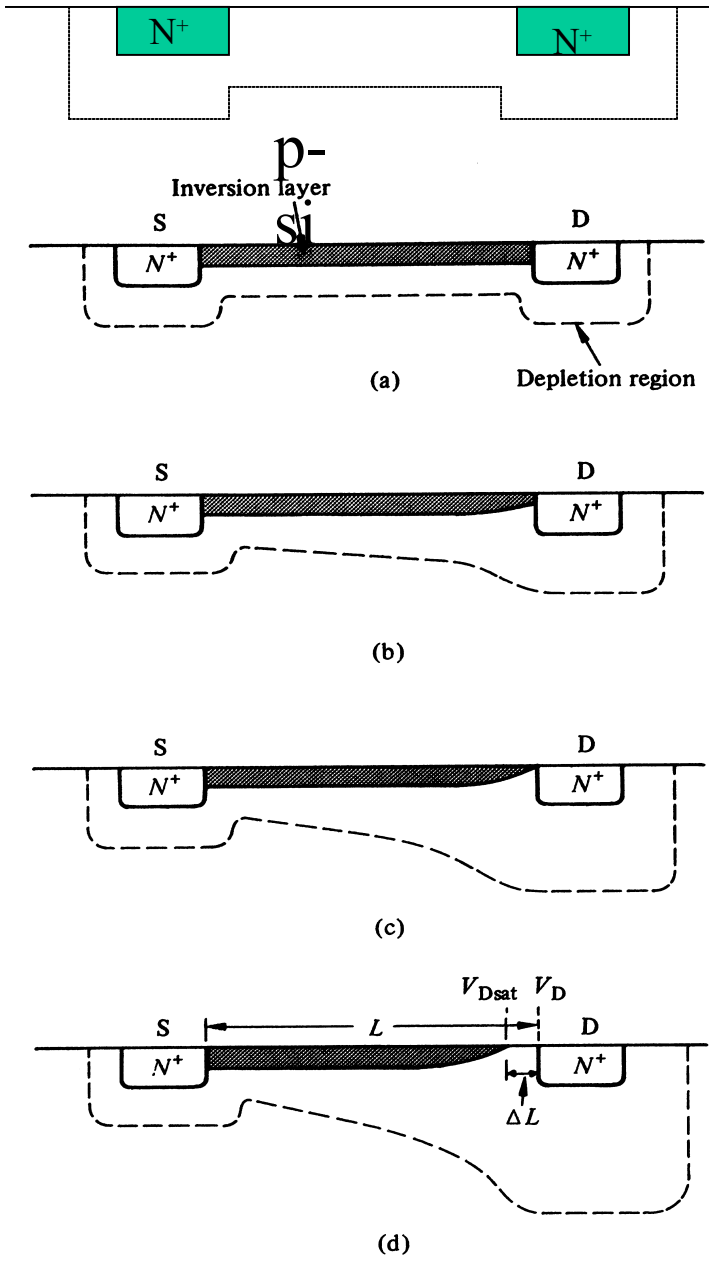
Quantitative I_D-versus-V_{DS} characteristics

Small-signal equivalent circuits.



N-channel MOSFET
Substrate: p-type Si

Qualitative discussion: NMOS



$0 < V_G < V_T$; V_{DS} small or large no channel, no current

$V_G > V_T$; $V_{DS} \approx 0$
I_D increases with V_{DS}

$V_G > V_T$; V_{DS} small, > 0
I_D increases with V_{DS} , but rate of increase decreases.

$V_G > V_T$; $V_{DS} \approx$ pinch-off
I_D reaches a saturation value, $I_{D,sat}$
The V_{DS} value is called $V_{DS,sat}$

$V_G > V_T$; $V_{DS} > V_{DS,sat}$
I_D does not increase further, saturation region.

I_D-V_{DS} characteristics for NMOS derived from qualitative discussions

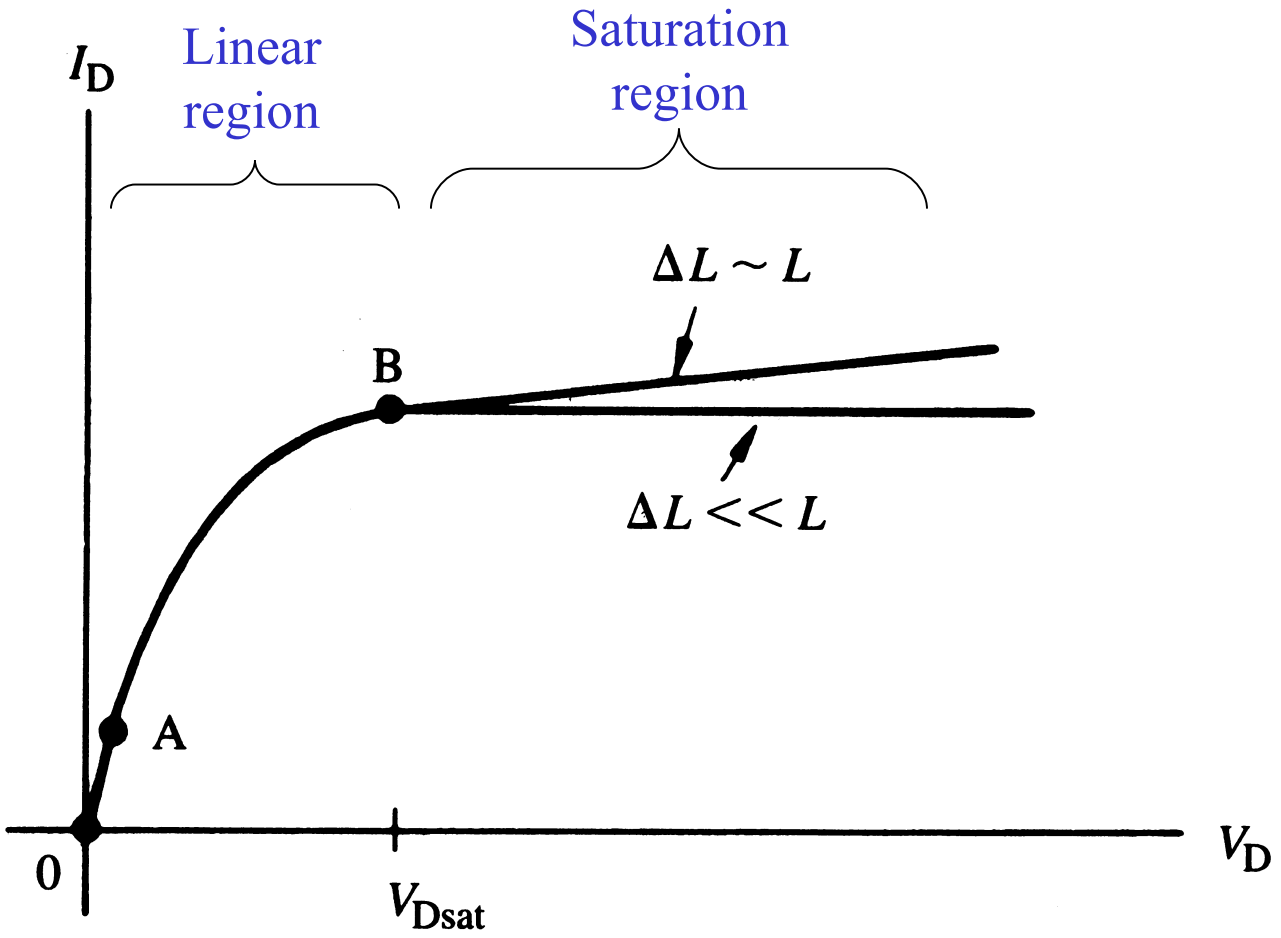


Figure 17.3

I_D-V_{DS} characteristics expected from a long channel ($\Delta L << L$) MOSFET (n-channel), for various values of V_G

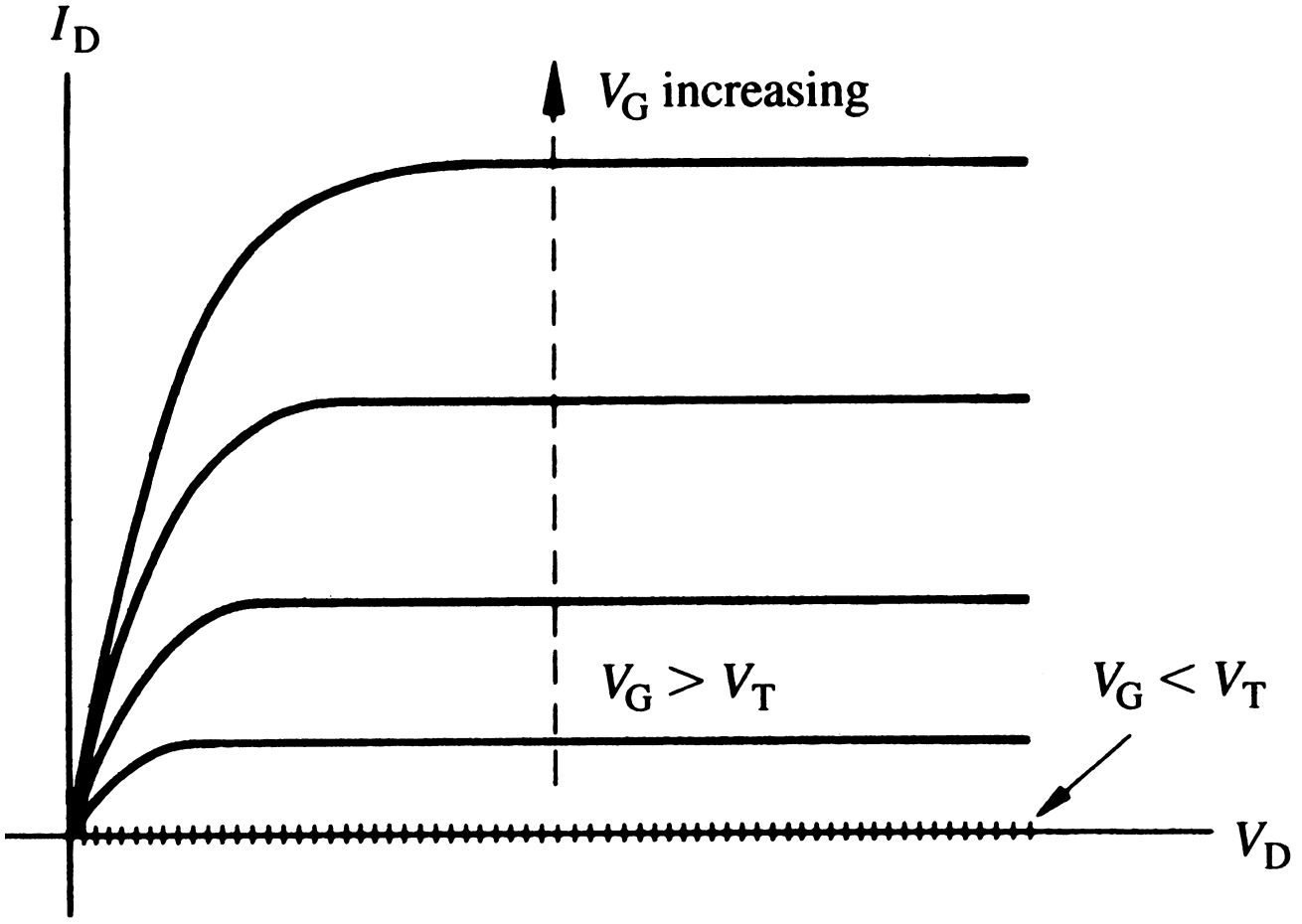


Figure 17.4

Threshold voltage for NMOS and PMOS

When $V_G = V_T$, $\phi_s = 2\,\phi_F$; using equation 16.28, we get expression for V_T.

$$V_T = 2\phi_F + x_{ox}\frac{\varepsilon_{Si}}{\varepsilon_{ox}}\sqrt{\frac{2qN_A}{\varepsilon_{Si}}2\phi_F}$$

Ideal n-channel (p-silicon) device both terms positive

$$V_T = 2\phi_F + \left(-x_{ox}\frac{\varepsilon_{Si}}{\varepsilon_{ox}}\sqrt{\frac{2qN_D}{\varepsilon_{Si}}|2\phi_F|}\right)$$

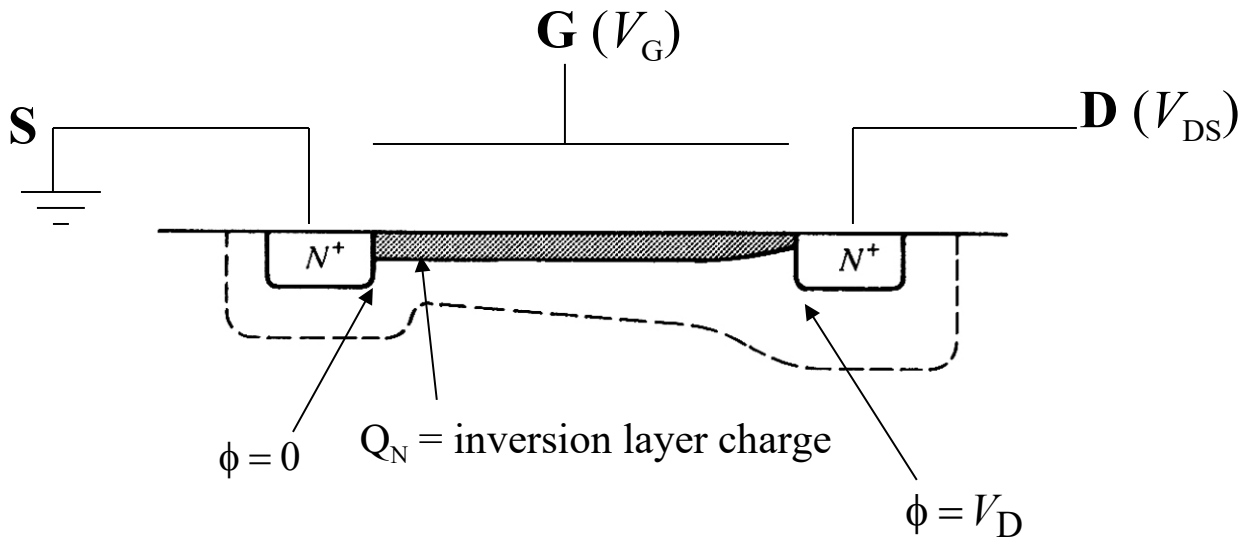
Ideal p-channel (n-silicon) device both terms negative

$$\varepsilon_{Si}/\varepsilon_{ox} = (\varepsilon_{r,Si}\,\varepsilon_0)/(\varepsilon_{r,ox}\,\varepsilon_0) = 11.9/3.9 \approx 3$$

$\varepsilon_{r,Si} = 11.9$ = relative dielectric constant of Si

ε_0 = absolute dielectric constant = 8.85×10^{-12} A s / (V m)

Quantitative I_D-V_{DS} relationships



Let ϕ be the potential along the channel

For $V_G < V_T$, Inversion layer charge is zero.

For $V_G > V_T$, $Q_n(y) = -Q_G = -C_{ox}(V_G - \phi - V_T)$

In general, $J_n = q\,\mu_n\,n\,\mathcal{E}$ when the diffusion current is neglected. Here, current I_D is the same everywhere, but J_n (current density) can vary from position to position.

Device structure, dimension, and coordinate orientations assumed in the quantitative analysis

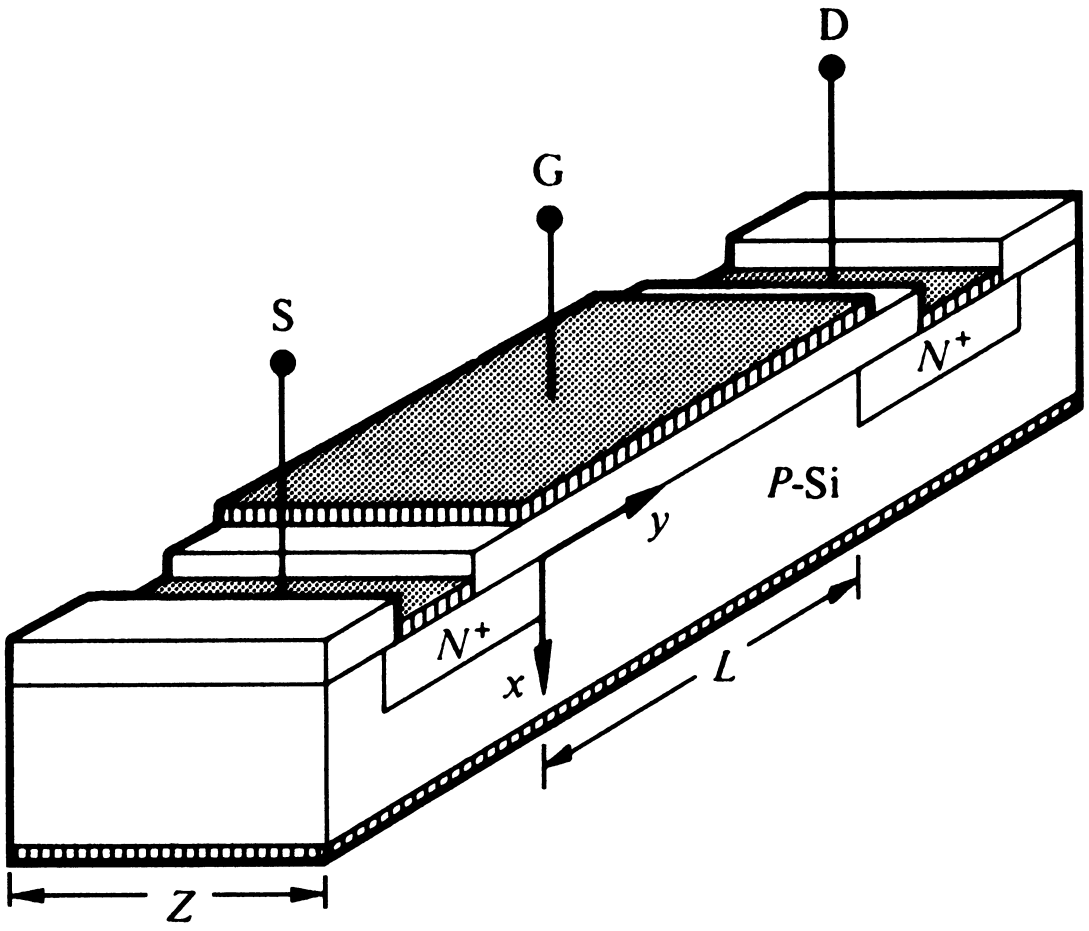


Figure 17.6

Quantitative I_D-V_{DS} relationships (Shockley model)

$$J_n = J_{ny} = q\mu_n n\mathcal{E} = -q\mu_n n\frac{d\phi}{dy} \qquad \text{since} \quad \mathcal{E}(y) = -\frac{d\phi}{dy}$$

To find current, we have to multiply the above with area, but J_{ny}, n, etc. are functions of x and z. Hence,

$$I_D = \int\int J_{ny}\,dx\,dz = Z\int J_{ny}\,dx = -Z\mu_n\frac{d\phi}{dy}\int qn\,dx$$

$$= -Z\mu_n\frac{d\phi}{dy}Q_n(y) \qquad Q_n(y) = \text{charge}/\text{unit area}$$

Integrating the above equation, and noting that I_D is constant, we get

$$I_D = -\frac{Z}{L}\mu_n\int_0^{V_{DS}} Q_n(y)\,d\phi$$

Since we know expression for $Q_n(y)$ in terms of ϕ, we can integrate this to get I_D

Quantitative I_D-V_{DS} Relationships (cont.)

$$I_D = \frac{Z\mu_n}{L} C_{ox} \left[(V_G - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] \qquad 0 < V_{DS} < V_{DS,sat} \;\; ; \;\; V_G > V_T$$

I_D will increase as V_{DS} is increased, but when $V_G - V_{DS} = V_T$, pinch-off of channel occurs, and current saturates when V_{DS} is increased further. This value of V_{DS} is called $V_{DS,sat}$. i.e., $V_{DS,sat} = V_G - V_T$ and the current when $V_{DS} = V_{DS,sat}$ is called $I_{DS,sat}$.

$$I_{D,sat} = \frac{Z \mu C_{ox}}{2L} (V_G - V_T)^2 \qquad V_D > V_{DS,sat} \;\; ; \;\; V_G > V_T$$

Here, C_{ox} is the oxide capacitance per unit area, $C_{ox} = \varepsilon_{ox} / x_{ox}$

Example 1

Plot the I_D vs. V_{DS} characteristics for an NMOS with the following parameters:

Substrate doping: 10^{16} cm^{-3}. Oxide thickness = 100 nm
Gate width = 15 μm; Gate length = 1 μm. Assume μ_n = 500 cm^2/(Vs)

Find C_{ox}: $C_{ox} = \varepsilon_{ox} / x_{ox} = 33.3$ nF/cm^2

$$V_T = 2\phi_F + x_{ox}\frac{\varepsilon_{Si}}{\varepsilon_{ox}}\sqrt{\frac{2qN_A}{\varepsilon_{Si}}2\phi_F} = 2.15\ \text{V}$$

$$I_{D,sat} = \frac{Z\mu C_{ox}}{2L}(V_G - V_T)^2 \qquad V_{DS} > V_{DS,sat} \quad ; \quad V_G > V_T$$

$$V_{DS,sat} = V_G - V_T$$

Find $I_{D,sat}$ for different values of V_G and plot the graph

Solution

$$N_A = n_i e^{(E_i - E_F)/kT}$$

$$q\phi_F = E_i - E_F$$

$$= kT \ln(\frac{N_A}{n_i})$$

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

$$= .026\text{V} \ln(\frac{10^{16}}{10^{10}})$$

$$= .359V$$

$$V_G = 3V$$

$$I_{D,sat} = \frac{Z\mu C_{ox}}{2L}(V_G - V_T)^2$$

$$= \frac{15 \times 10^{-4}\text{cm} \cdot 500\text{cm}^2/\text{Vs} \cdot 33 \times 10^{-9}\text{F/cm}^2}{2 \cdot 1 \times 10^{-4}\text{cm}}(3\text{V} - 2.15\text{V})^2$$

$$= 89.4\mu A$$