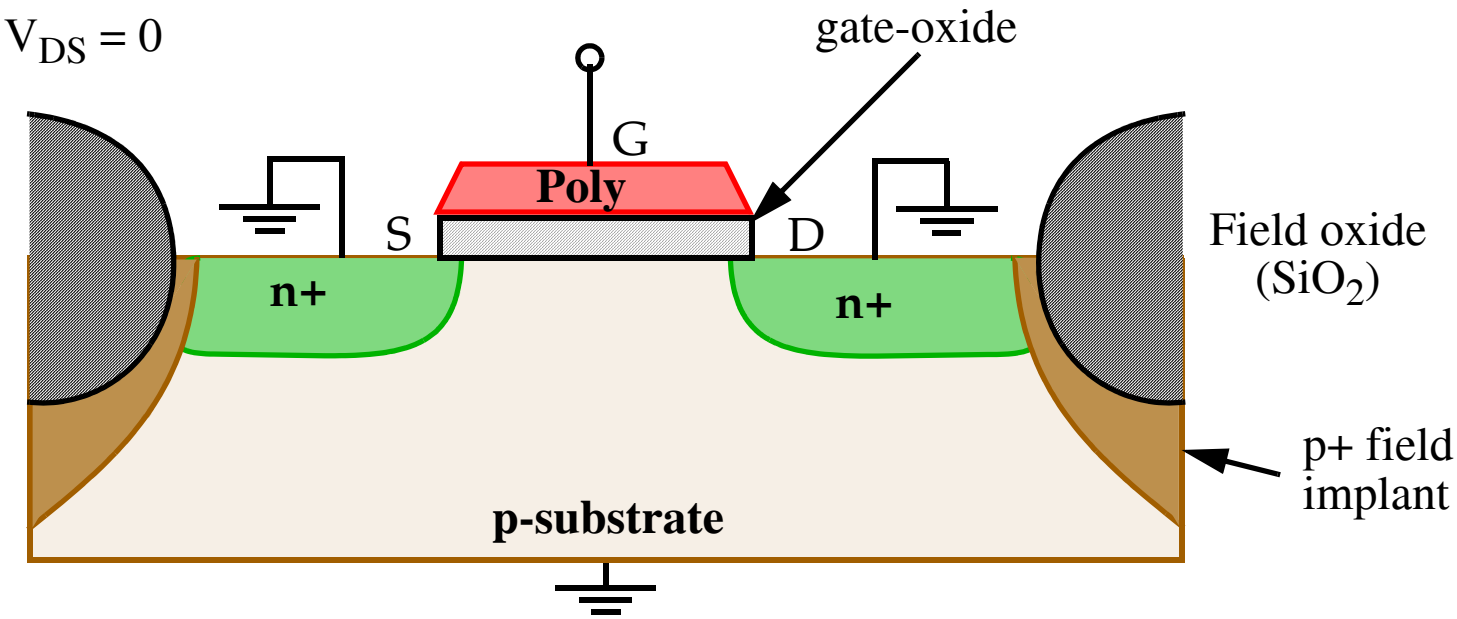
Static Behavior

An **nMOS** transistor cross-section:

$V_{GS} = 0, V_{DS} = 0$



Under zero bias, two back-to-back *pn*-junctions create a very high resistive path between source and drain.

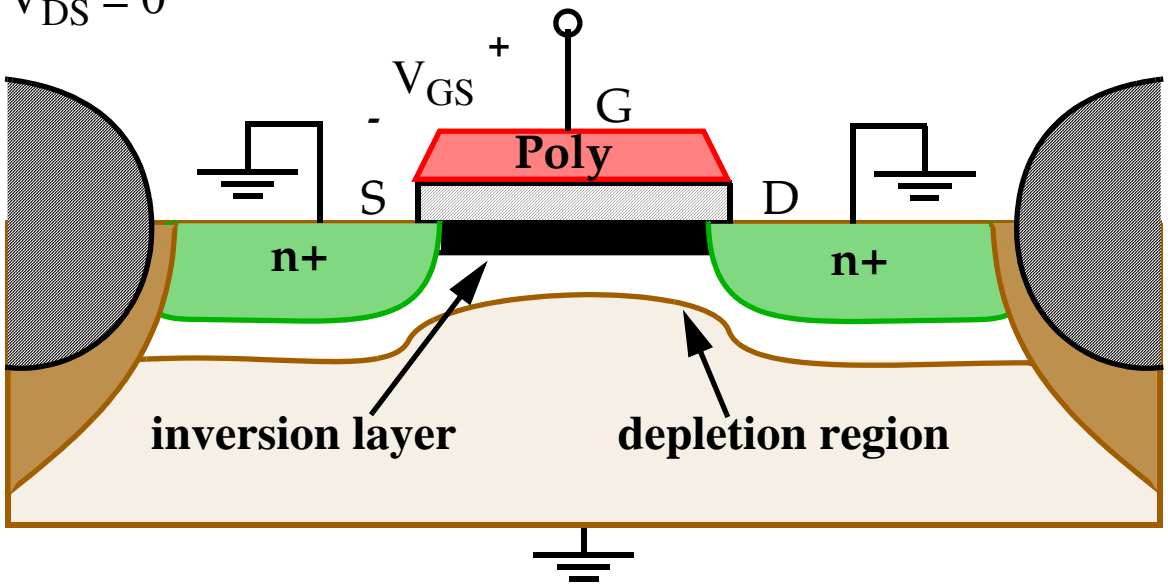
Appling a **positive bias** (V_{GS}) to the gate (w.r.t. the source), creates a depletion region under the gate (repells mobile holes).

The depletion region is similar to the one occurring in a *pn*-junction.

Static Behavior

Inversion

$V_{GS} > 0, V_{DS} = 0$



Depletion region expressions are similar to the diode expressions:

$$W_d = \sqrt{\frac{2\varepsilon_{si}\phi}{qN_A}}$$ Width

$$Q_d = \sqrt{2N_A\varepsilon_{si}\phi}$$ Space charge

ϕ = potential at the oxide-silicon boundary

Static Behavior

Inversion

At a critical value of V_{GS}, the substrate **inverts** to *n-type* material.

This is called strong inversion and occurs at a voltage that is twice the *Fermi Potential*:

$\phi_F = -0.3V$ for typical p-type silicon substrates.

Further increases in V_{GS} do **not** increase the depletion layer width.

The charge is offset with additional inversion-layer electrons (sourced from the heavily doped *n*+ source region).

The *conductivity* of the n-channel is modulated by V_{GS}.

Under strong inversion, the *charge* in the depletion region is fixed and equals:

$$Q_{B0} = \sqrt{2qN_A\varepsilon_{si}\left|-2\phi_F\right|}$$

Static Behavior

Inversion

A substrate bias voltage, V_{SB}, **increases** the surface potential needed to create strong inversion to:

$$\left| -2\phi_F + V_{SB} \right|$$

V_{SB} is normally positive for n-channel devices.

This changes the charge in the depletion region:

$$Q_B = \sqrt{2qN_A\varepsilon_{si}\left| -2\phi_F + V_{SB} \right|}$$

The value of V_{GS} where strong inversion occurs is ***threshold voltage***, V_T.

V_T depends on several components, many are material constants:

- difference in work function between gate and substrate material.
- oxide thickness
- Fermi voltage
- charge associated with impurities trapped at oxide-channel interface
- concentration of implanted ions

Static Behavior

V_T also depends substrate voltage, V_{SB}.

Rather than depend on the complete analytical form (which often is not a good predictor of V_T), an empirical parameter is used, V_{T0}.

V_{T0} is the threshold voltage with $V_{SB} = 0$.

$$V_T = V_{T0} + \gamma\left(\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|}\right)$$

V_T is **positive** for **nMOS** and **negative** for **pMOS**

$$\gamma = \frac{\sqrt{2q\varepsilon_{si}N_A}}{C_{ox}}$$

(γ is the *body effect* coefficient)

γ expresses the impact of changes in V_{SB}.

A negative bias on the well or substrate causes V_T to **increase**.

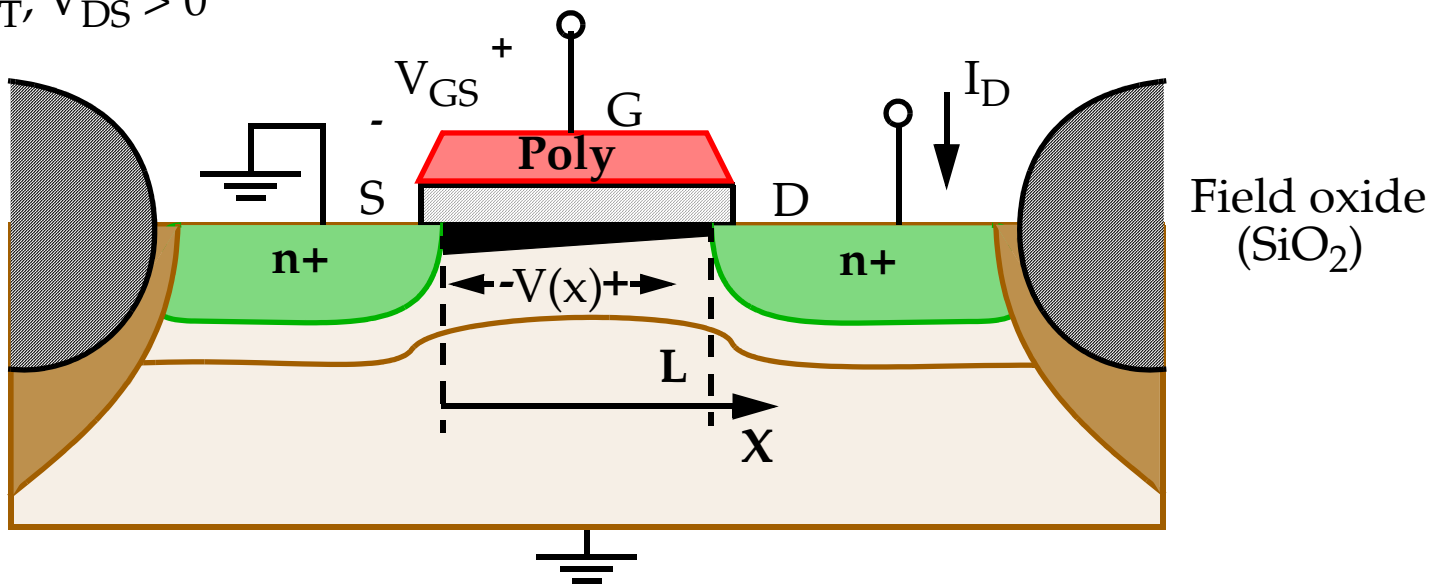
Given: $V_{T0} = 0.75V$ $\gamma = 0.54$ $2\phi_F = -0.64V$ $V_{SB} = 5V$

$$V_T = 0.75 + 0.54\left(\sqrt{|-2(-0.6) + 5V|} - \sqrt{|-2(-0.6)|}\right) = 1.6V!$$

Static Behavior

Current-Voltage Relations

$V_{GS} > V_T, V_{DS} > 0$



- **Linear Region**

At a point x along the channel, the voltage is V(x).

The gate-to-channel voltage at that point equals V_{GS} -V(x).

Static Behavior

Linear region

Assume that this voltage exceeds the threshold everywhere along the channel.

The *induced channel* charge per unit area at point x is:

$$Q_i(x) = -C_{ox}[V_{GS} - V(x) - V_T]$$

The gate capacitance per unit area, C_{ox}, is expressed as:

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \qquad \varepsilon_{ox} = 3.97 \times \varepsilon_0 = 3.5 \times 10^{-13} \text{F/cm}$$

t_{ox} is *gate oxide thickness*.

It is 10 nm or smaller in contemporary processes.

For t_{ox} = 5 nm, C_{ox} is 7 fF/um^2.

Static Behavior

Linear region

Current is given as the product of the *drift velocity* of the carriers and the available *charge*:

$$I_D = -\upsilon_n(x)Q_i(x)W$$

υ_n = drift velocity

W = width of channel

The **electron velocity**, υ, is related to the electric field through a parameter called the mobility (μ):

$$\upsilon_n = -\mu_n E(x) = \mu_n \frac{dV}{dx}$$

Combining the equations:

$$I_D dx = \mu_n C_{ox} W(V_{GS} - V - V_T)dV$$

Static Behavior

Linear region

Integrating this equation over the length of the channel yields the *current-voltage* relationship of a nMOS transistor.

$$I_D = k_n' \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \qquad (1)$$

$$k_n = k_n' \frac{W}{L} \qquad \text{(gain factor)}$$

$$k_n' = \mu_n C_{ox} = \frac{\mu_n \varepsilon_{ox}}{t_{ox}} \qquad \text{(process transconductance parameter)}$$

For typical n-channel devices with: $t_{ox} = 20\text{nm}$

$$k_n' = 80\mu A/V^2$$

For small values of V_{DS}, the quadratic factor can be ignored and we observe a linear relationship between V_{DS} and I_D.

NOTE: W and L are *effective* width and length, not the drawn values.

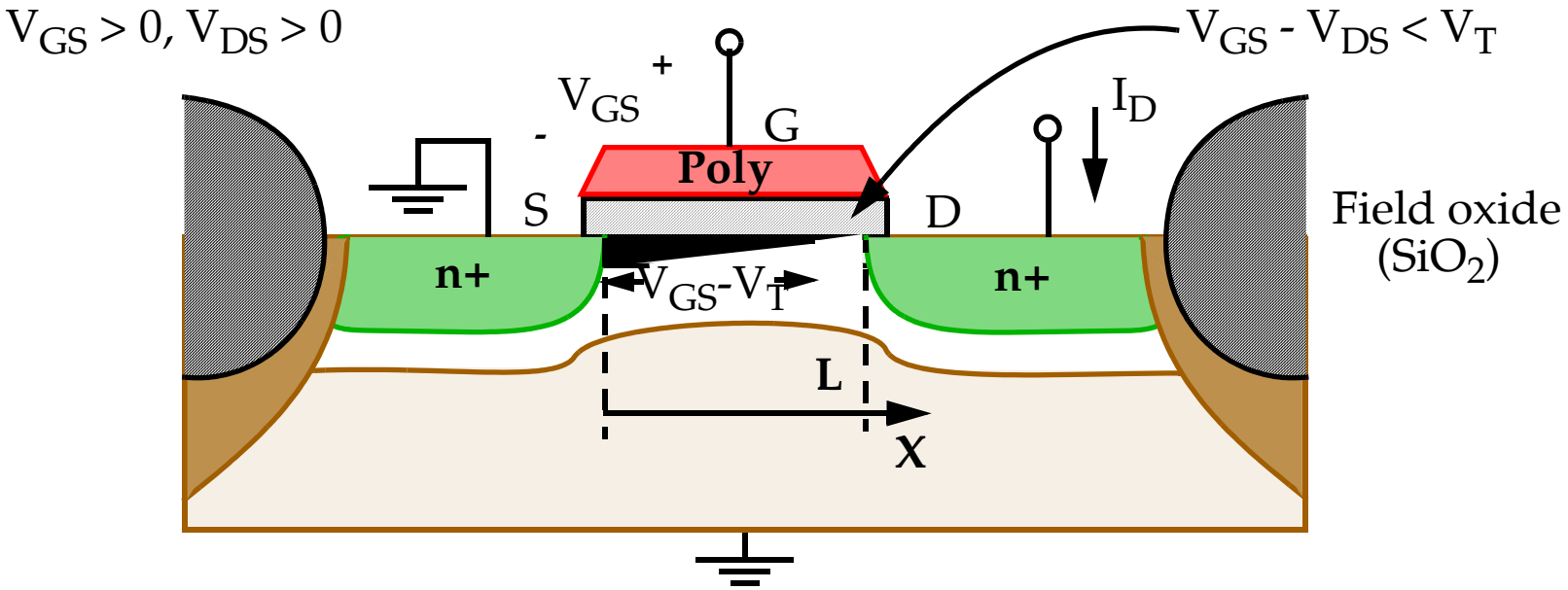
Static Behavior

Saturation

When V_{DS} is further increased, the channel voltage all along the channel may **cease** to be larger than the threshold, e.g.,

$$V_{GS} - V(x) < V_T$$

At that point, the induced charge is zero and the channel disappears or is *pinched off*.



Static Behavior

Current-Voltage Relation: Saturation

The voltage difference over the *induced channel* remains fixed at V_{GS} - V_T and the current remains constant (or **saturates**).

Replacing V_{DS} with V_{GS} - V_T in equation (1) (since this equation was derived over the channel) yields:

$$I_D = \frac{k_n'}{2}\frac{W}{L}(V_{GS} - V_T)^2 \qquad (2)$$

This equation is not entirely correct, since the channel length changes as a function of V_{DS}.

Current **increases** as channel length (L) **decreases**, according to equation (2).

A more accurate expression for current in saturation is:

$$I_D = \frac{k_n'}{2}\frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

λ: empirical parameter called *channel-length modulation*

Static Behavior

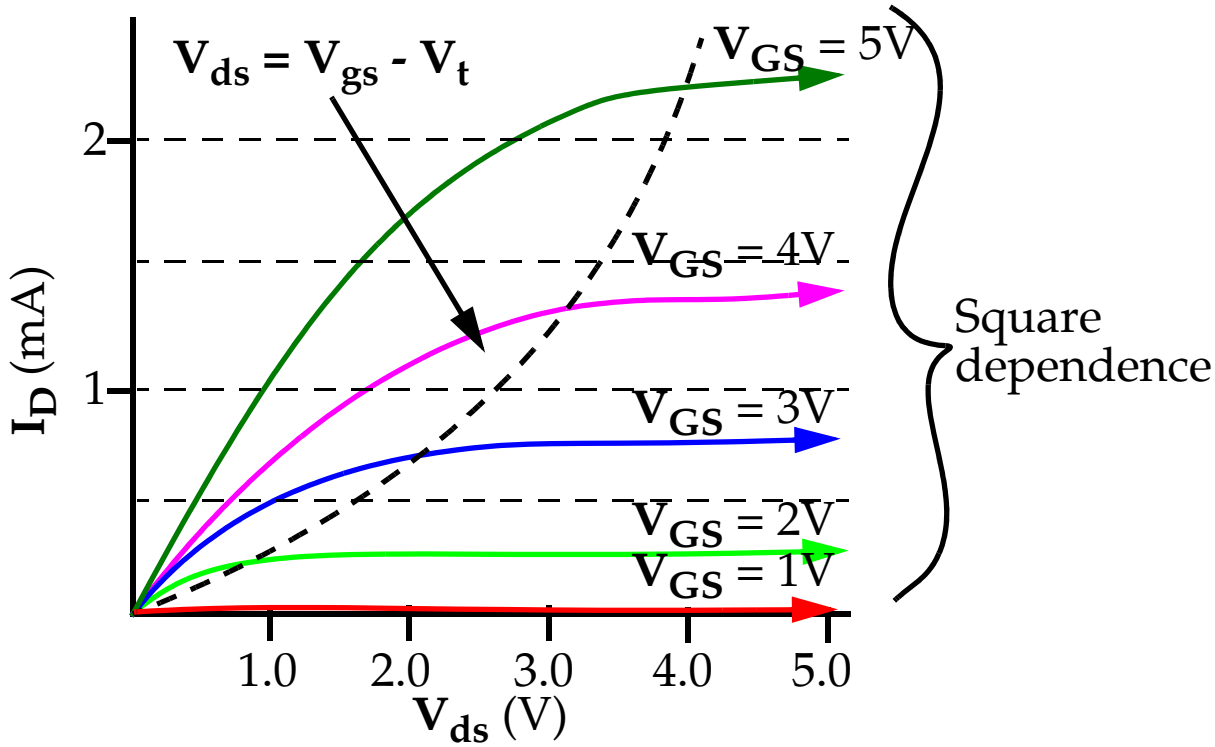
Current-Voltage curves

I-V **nMOS** transistor curves for a device with dimensions:

$W = 100\mu m$

$L = 20\mu m$

in a 1.2µm process.



Static Behavior

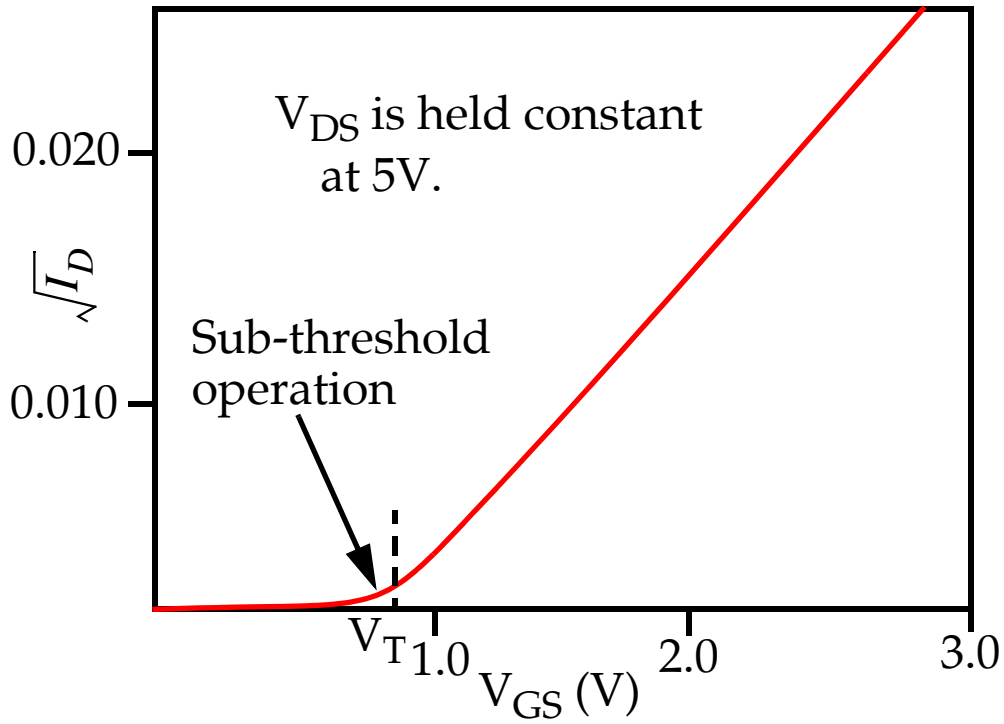
Current-Voltage Relation

Triode region: The transistor behaves like a voltage-controlled resistor.

Saturation region: It behaves like a voltage-controlled current source (ignoring channel-length modulation effects).

Linear relationship for values:

$V_{GS} > \ > V_T$

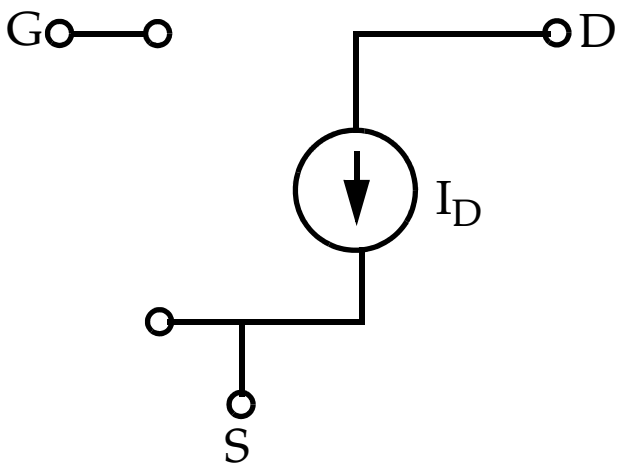


Note: Analytical expressions of λ have proven inaccurate.

Device experiments indicate that λ varies ~ 1/channel length.

Static Behavior

Manual Analysis Model



$$V_{DS} > V_{GS} - V_T$$

$$I_D = \frac{k_n'}{2}\frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda V_{DS})$$

$$V_{DS} < V_{GS} - V_T$$

$$I_D = k_n'\frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

with

$$V_T = V_{T0} + \gamma\left(\sqrt{\left|-2\phi_F + V_{SB}\right|} - \sqrt{\left|-2\phi_F\right|}\right)$$