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# MOSFET:
# Long Channel (3)

Lecture 9

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# Outline

Long Channel:

- Subthreshold Regime:
  - Subthreshold Current
  - Subthreshold Swing

High Field Effects:

- Velocity Saturation: Lateral Field Effect on Mobility



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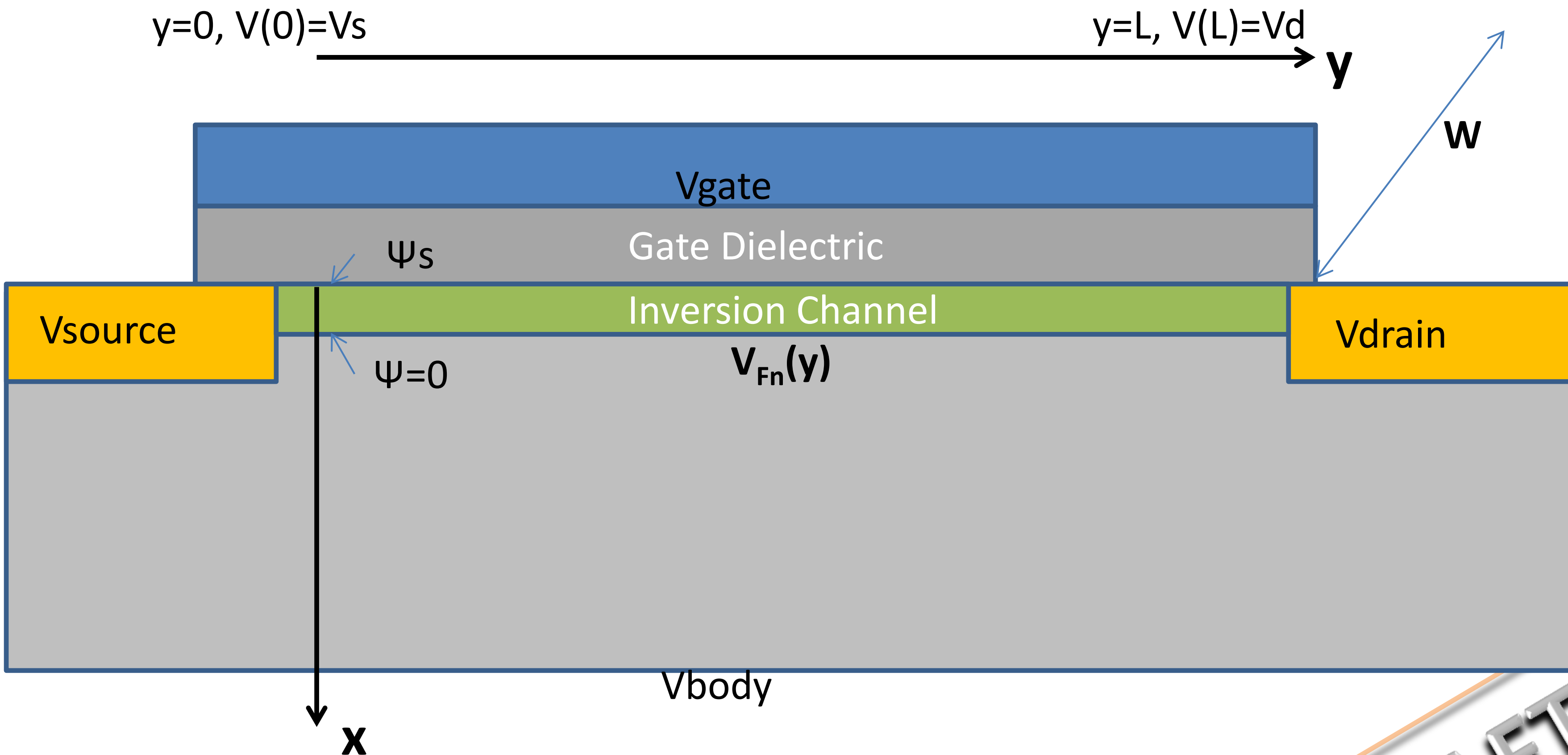
# MOSFET

$$J_n = -q\, n(x,y)\, \mu_n \frac{d}{dy}[V(y)]$$



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# Subthreshold Regime: $V_{gs}<V_t$, $\Psi_s<2\Psi_B$

- *Diffusion component of current dominates*

$$-Qs = -QD - Qi = \epsilon_{Si}\, Es = \sqrt{2\epsilon_{si} kTN_A}\left[\frac{q\Psi_s}{kT} + \frac{{n_i}^2}{{N_A}^2} e^{q[\Psi s - V(y)]/kT}\right]^{1/2}$$

Using series expansion of : $(1+a)^{1/2} = 1 + a/2 - a^2/8 + \cdots..$

$$-Qi = \sqrt{\frac{\epsilon_{si} qN_A}{2\Psi s}}\left(\frac{kT}{q}\right)\left(\frac{{n_i}^2}{{N_A}^2}\right) e^{q[\Psi s - V(y)]/kT}$$

Using: $I_{ds} = \mu_{neff}\frac{W}{L}\int_0^{Vds} Q_i(y)\, dV(y)$

$$I_{ds} = \mu_{neff}\frac{W}{L}\sqrt{\frac{\epsilon_{si} qN_A}{2\Psi s}}\left(\frac{kT}{q}\right)^2\left(\frac{n_i}{N_A}\right)^2 e^{q\Psi s/kT}\left[1 - e^{-qVds/kT}\right]$$



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# Subthreshold Regime (2): $V_{gs}<V_t$, $\Psi_s<2\Psi_B$

Using: $V_{gate} = VFB - \frac{Q_s}{C_{ox}} + \Psi_s$

And keeping only depletion charge ($\Psi_s < 2\Psi_B$)

$$V_{gs} = VFB + \frac{\sqrt{2\varepsilon_{si} q N_A \Psi_s}}{C_{ox}} + \Psi_s$$

Approximation: $\Psi_s$ is sligltly less than $2\Psi_B \rightarrow$ Expand $\sqrt{\Psi s}$ using series at $\Psi_s=2\Psi_B$ :

$$V_{gs} = VFB + \frac{\sqrt{4\varepsilon_{si} q N_A \Psi_B}}{C_{ox}} + \left[1 + \frac{\sqrt{\varepsilon_{si} q N_A / 4\Psi_B}}{C_{ox}}\right](\Psi_s - 2\Psi_B)$$

Using: $V_t = VFB + (2m-1)(2\Psi_B)$

$$I_{ds} = \mu_{neff} C_{ox} \frac{W}{L} (m-1) \left(\frac{kT}{q}\right)^2 e^{\frac{q(V_{gs}-Vt)}{mkT}} \left[1 - e^{-qVds/kT}\right]$$

At Vgs=0, *$I_{ds\ Off}$=Off-state leakage current* $\approx I_o \exp(-qVt/mkT)$

-> *Ids leakage increase exponentially with decreasing Vt*



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# Subthreshold Slope

$$S = \left(\frac{d\ log_{10}\ Ids}{dV_{gs}}\right)^{-1} = 2.3\left(\frac{m\ kT}{q}\right) = 2.3\left(\frac{kT}{q}\right)\left(1 + \frac{C_{dm}}{C_{ox}}\right)$$

Expressed in mV/decade (typically 70-100mV/decade)

Good switching requires small S

Note: $\ln(x) = 2.3 \log_{10}(x)$

Exercise:

Derive this relationship



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# Temperature Effects on Vt

$$V_t = V_{FB} + \frac{\sqrt{2\varepsilon_{si} q N_A (2\Psi_B)}}{C_{ox}} + 2\Psi_B$$

$$V_{FB} = -\frac{E_g}{2q} - \Psi_B \rightarrow Vt = -\frac{E_g}{2q} + \frac{\sqrt{2\varepsilon_{si} q N_A (2\Psi_B)}}{C_{ox}} + \Psi_B$$

$$\frac{dV_t}{dT} = -\frac{1}{2q}\frac{dE_g}{dT} + \left(1 + \frac{\sqrt{\varepsilon_{si} q N_A / \Psi_B}}{C_{ox}}\right)\frac{d\Psi_B}{dT} = -\frac{1}{2q}\frac{dE_g}{dT} + (2m-1)\frac{d\Psi_B}{dT}$$

Using:

$$\Psi B = kT\, ln(N_A/n_i) = kT\, ln(N_A/(\sqrt{N_c N_v} e^{-Eg/kT})$$

$$N_c N_v = Nc_0 N_{v0} (T/300)^3$$

$$\frac{dV_t}{dT} = -(2m-1)\frac{k}{q}[\ln\left(\frac{\sqrt{N_c N_v}}{N_A}\right) + 3/2] + \frac{m-1}{q}\frac{dEg}{dT}$$



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# Temperature Effects on Vt and Subthreshold Leakage Current

- dVt/dT ranges from -0.7mV/K to -1mV/K
- At 100C:
  - Vt decreases by 55 to 75mV w.r.t room temperature
  - Isub increases by a factor of 30-50 w.r.t room T



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# Negative Substrate Bias ($-V_{bs}$ )Effect on Vt

At –Vbs applied to substrate w.r.t. source:

$$Vgs, \quad Vs = 0, \quad Vds, \quad -Vbs$$

$$\rightarrow Vgs + Vbs, \quad Vs = +Vbs, \quad Vds + Vbs, \quad Vb = 0$$

$$V_t = VFB + \frac{\sqrt{2\varepsilon_{si} q N_A (2\Psi_B + Vbs)}}{C_{ox}} + 2\Psi_B$$

$$\frac{dV_t}{dV_{bs}} = \frac{\sqrt{\varepsilon_{si} q N_A / 2(2\Psi_B + Vbs)}}{C_{ox}}$$

Depletion Width $W_{dm}$ widens



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