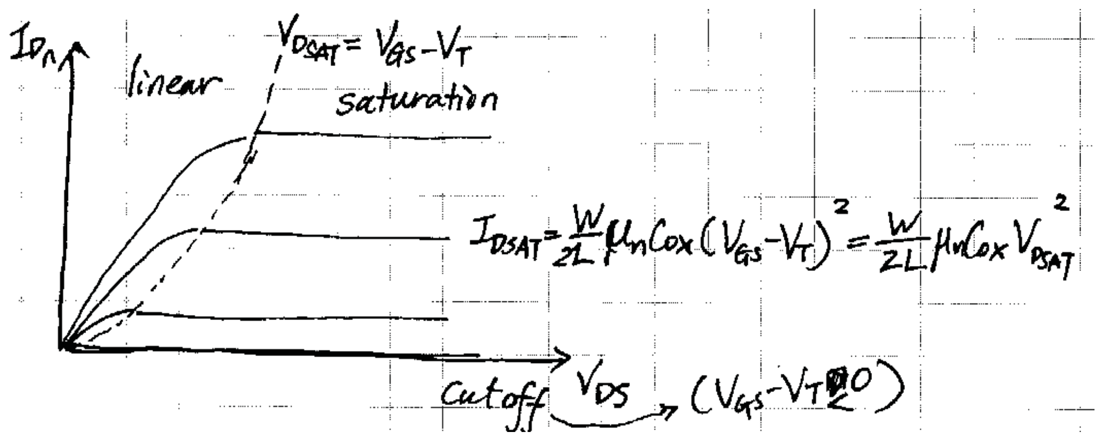
Recitation 10: MOSFET VI Characteristics - Channel Length Modulation & Back Gate Effect

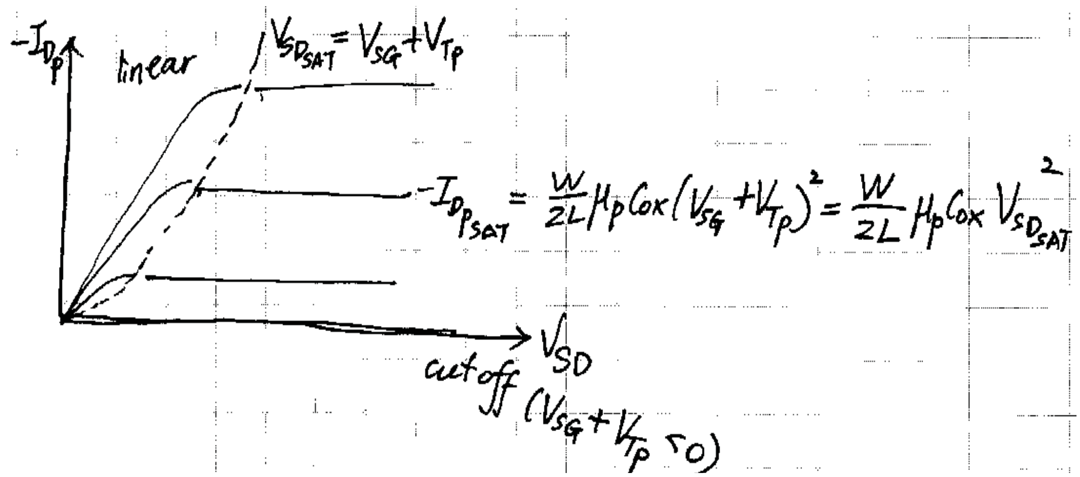
Yesterday we discussed two more aspects in MOSFET IV characteristics.

- Channel length modulation
- Backgate effect

Here is the n-MOS IV characteristic (ideal, no channel length modulation)



What about the IV characteristic for a p-MOS?

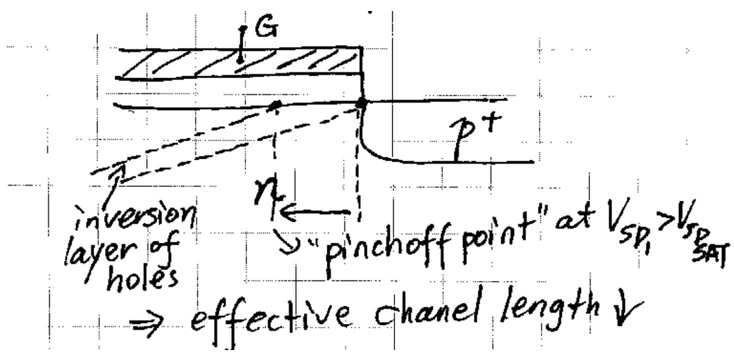


Channel Length Modulation

NMOS

What happens when $V_{\mathrm{DS}} = V_{\mathrm{GS}} - V_{\mathrm{T}}$?

$$|Q_{\mathrm{n}}(L)| = C_{\mathrm{ox}}(V_{\mathrm{GS}} - V_{\mathrm{DS}} - V_{\mathrm{T}}) = 0$$

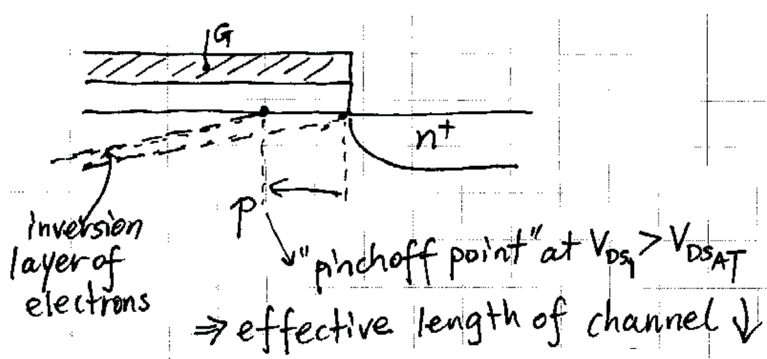


$$I_{\mathrm{DS}} = \frac{w}{2L}\mu_{\mathrm{n}} C_{\mathrm{ox}}(V_{\mathrm{GS}} - V_{\mathrm{T}})^2 \quad L \downarrow I_{\mathrm{DS}} \uparrow$$

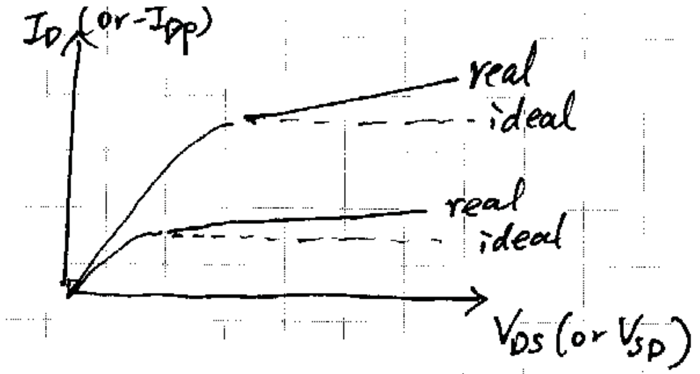
PMOS

When $V_{\mathrm{SD}} = V_{\mathrm{SG}} + V_{\mathrm{T_p}}$,

$$|Q_{\mathrm{p}}(L)| = C_{\mathrm{ox}}(V_{\mathrm{SG}} - V_{\mathrm{SD}} + V_{\mathrm{T_p}}) = 0$$



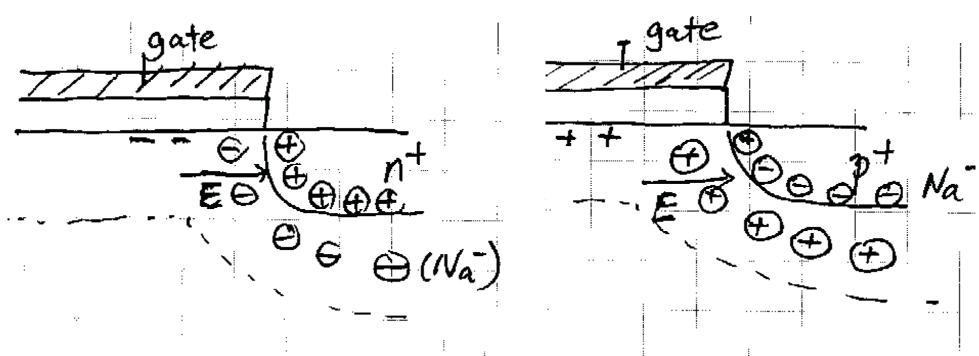
As a result,



To model it, we have:

$$\begin{aligned}
I_{\mathrm{D}} &\simeq \frac{w}{2L}\mu_{\mathrm{n}}C_{\mathrm{ox}}(V_{\mathrm{GS}}-V_{\mathrm{T}})^2(1+\lambda V_{\mathrm{DS}}) \\
(\text{or } -I_{\mathrm{D_p}} &\simeq \frac{w}{2L}\mu_{\mathrm{p}}C_{\mathrm{ox}}(V_{\mathrm{SG}}+V_{\mathrm{T_p}})^2(1+\lambda V_{\mathrm{SD}})) \\
\text{e.g.}\, \lambda &= \frac{0.1\,\mu\mathrm{m}}{L}V^{-1}
\end{aligned}$$

The ideal case is the ideal current source, now we have a current source with some internal resistance (will talk about this later).
Note: pinch-off region does not impede current flow near drain (high lateral E-field near drain makes them go fast)



Backgate Effect

NMOS

When $V_{\mathrm{BS}} = 0$,

$$
\begin{aligned}
V_{\mathrm{T}} &= V_{\mathrm{FB}} - 2\phi_{\mathrm{p}} + \frac{1}{C_{\mathrm{ox}}}\sqrt{2\epsilon_{\mathrm{s}} q N_{\mathrm{a}}(-2\phi_{\mathrm{p}})} \\
(V_{\mathrm{FB}} &= -(\phi_{\mathrm{gate}} - \phi_{\mathrm{body}}))
\end{aligned}
$$

When $V_{\mathrm{BS}} < 0$,

$$
V_{\mathrm{T}}(V_{\mathrm{BS}}) = V_{\mathrm{FB}} - 2\phi_{\mathrm{p}} + \frac{1}{C_{\mathrm{ox}}}\sqrt{2\epsilon_{\mathrm{s}} q N_{\mathrm{a}}(-2\phi_{\mathrm{p}} - V_{\mathrm{BS}})}
$$

Backgate effect parameter:

$$
\begin{aligned}
\gamma &= \frac{1}{C_{\mathrm{ox}}}\sqrt{2\epsilon_{\mathrm{s}} q N_{\mathrm{a}}} \\
V_{\mathrm{T}}(V_{\mathrm{BS}}) &= V_{\mathrm{TO}} + \gamma(\sqrt{-2\phi_{\mathrm{p}} - V_{\mathrm{BS}}} - \sqrt{-2\phi_{\mathrm{p}}})
\end{aligned}
$$

PMOS

When $V_{\mathrm{BS}} = 0$,

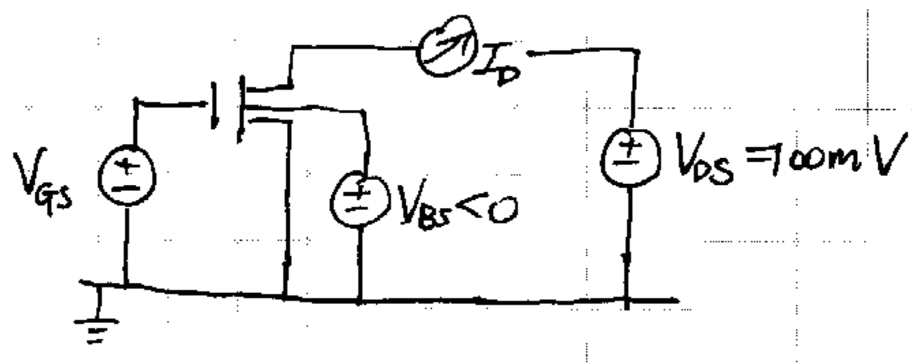
$$
\begin{aligned}
V_{\mathrm{T_p}} &= V_{\mathrm{FB}} - 2\phi_{\mathrm{n}} - \frac{1}{C_{\mathrm{ox}}}\sqrt{2\epsilon_{\mathrm{s}} q N_{\mathrm{d}}(+2\phi_{\mathrm{n}})} \\
(V_{\mathrm{FB}} &= -(\phi_{\mathrm{gate}} - \phi_{\mathrm{body}}))
\end{aligned}
$$

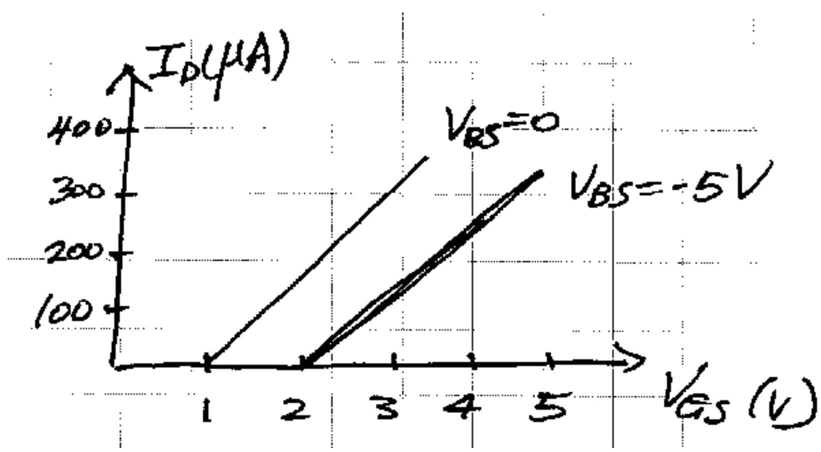
When $V_{\mathrm{SB}} < 0$, or $V_{\mathrm{BS}} > 0$

$$
\begin{aligned}
V_{\mathrm{T_p}}(V_{\mathrm{SB}}) &= V_{\mathrm{FB}} - 2\phi_{\mathrm{n}} - \frac{1}{C_{\mathrm{ox}}}\sqrt{2\epsilon_{\mathrm{s}} q N_{\mathrm{d}}(2\phi_{\mathrm{n}} - V_{\mathrm{SB}})} \\
\gamma &= \frac{1}{C_{\mathrm{ox}}}\sqrt{2\epsilon_{\mathrm{s}} q N_{\mathrm{d}}} \\
V_{\mathrm{T_p}}(V_{\mathrm{SB}}) &= V_{\mathrm{T_{po}}} - \gamma(\sqrt{2\phi_{\mathrm{n}} - V_{\mathrm{SB}}} - 2\sqrt{\phi_{\mathrm{n}}})
\end{aligned}
$$

Exercise

NMOS, channel doping $N_a = 10^{17}\, cm^{-3}$





V_{GS} vary from $0 \to 5\,\mathrm{V}$, $\mathrm{V_{BS}} = 0, -5\,\mathrm{V}$. $V_{T_n} = 10\,\mathrm{V}$ when $V_{BS} = 0; V_{T_n} = 2\,\mathrm{V}$ when $V_{BS} = -5\,\mathrm{V}$. What is γ_n? What is C_{ox}?

$$\begin{aligned}
\gamma_n &= \frac{1}{C_{ox}}\sqrt{2\epsilon_s q N_a} \text{ to find } \gamma_n \text{, need to know } C_{ox} \\
V_{T_n}(V_{BS}) &= V_{T_{no}} + \gamma_n(\sqrt{-2\phi_p - V_{BS}} - \sqrt{-2\phi_p}) \quad \phi_p = -0.42\,\mathrm{V} \\
2\,\mathrm{V} &= 1\,\mathrm{V} + \gamma_n(\sqrt{0.84\,\mathrm{V} + 0.5\,\mathrm{V}} - \sqrt{0.84\,\mathrm{V}}) \implies \gamma_n = 0.67\,\mathrm{V}^{\frac{1}{2}} \\
C_{ox} &= \frac{1}{\gamma_n}\sqrt{2\epsilon_s q N_a} = \frac{1}{0.67\,\mathrm{V}^{\frac{1}{2}}}\sqrt{2 \times 1 times 10^{-12}\,\mathrm{F/cm} \times 1.6 \times 10^{-19}\,\mathrm{C} \times 10^{17}\,\mathrm{cm}^{-3}} \\
&= 2.7 \times 10^{-7}\,\mathrm{F/cm^2}
\end{aligned}$$

When $V_{GS} = 3\,\mathrm{V}, \mathrm{V_{DS}} = 0.1\,\mathrm{V}, \mathrm{V_{BS}} = 0\,\mathrm{V}$, what is the channel electron charge density at the drain?

$$|Q_n(L)| = C_{ox}(V_{GS} - V_{T_{n_o}} - V_{DS}) = 2.7 \times 10^{-7}\,\mathrm{F/cm^2} \times (3 - 1 - 0.1)\,\mathrm{V} =$$

When $V_{DS} = 0.1\,\mathrm{V}, \mathrm{V_{GS}} = 3\,\mathrm{V}, \mathrm{V_{BS}} = -5\,\mathrm{V}$, what is the channel electron charge density at the drain?

$$|Q_n(L)| = C_{ox}(V_{GS} - V_{T_n}(V_{BS}) - V_{DS}) =$$

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