MOSFETs (or MISFETs to be general)

To understand MOSFETs, we must first understand MOS capacitors.

Again, this course is about the big picture
The gate could be heavily doped Si, or a true metal. Al work function $\sim 4.1 \text{ eV}$, about mid gap.
Equil.: $E_f$'s line up.

- Energy differences indicated by doubled-headed arrows remain unchanged.
  (Ignoring surface states)

Band (potential) profiles are linear in SiO$_2$ (Why?)

Band bending in Si (Why?)
Now, apply a negative $V_g$

The surface (SiO$_2$-Si interface) is more p than the bulk.

-- Accumulation

This band bending is different from that in depletion
Positive gate bias.

Near the interface, less $p$ than the bulk.

- Depletion

Depletion approx.

$$x_d = \sqrt{\frac{2 e \varepsilon E_x \Phi_0}{q N_A}}$$

The depletion region charge $Q_d = q N_A x_d$ (per cross-section area)
Increase the positive $V_g$.

- Enough electrons to screen the E field
- $x_d$ can no longer widen
- $Q_{d_{\text{max}}} = \rho N_A x_{d_{\text{max}}}$

The $V_g$ corresponding to $x_d$ is $V_{th}$, after which
After $x_{d_{\text{max}}}$ is reached

\[ qn = C_\text{ox} (V_G - V_{\text{th}}) \]

Every volt of increase in $V_G$ is used to induce more e's.

Of course, $V_{\text{th}}$ is not well defined

Subthreshold: $\Delta V_G$ is used to widen $x_d$, adding few e's.
High frequency curve assuming no S/D, but only a body contact.
What if there is a S contact?

Why did the industry go back to metal gates?
Voltage division between the dielectric and the semiconductor

Voltage division

\[ \phi_i = \frac{C_{ox} V}{C_{ox} + C_d} \]

In the depletion regime (i.e., sub-threshold) while \( \phi_d \) being widened, \( n \) does increase, since \( E_F \) moves.

\[ n \propto e^{\frac{q \phi_i}{kT}} \]
Is there a way to make this slope steeper?
Again, $V_{th}$ is **NOT** well defined.

**Common definition of $V_{th}$:**

The $V_{th}$ that makes the surface to be $n$ as much as the bulk is $p$.

Kind of arbitrary.
Use Gauss’s law to think about this.
The MOSFET is a 4-terminal device.

Body effect varies $V_{th}$ (only!).

When $V_D$ is very small, the channel is almost uniform from $S$ to $D$.

$s = \frac{\rho n L}{\mu}$

The channel is just a $V_G$-controlled resistor.
the channel is almost uniform from S to D.

\[ \sigma = q n \mu \]

The channel is just a \( V_G \)-controlled resistor.

Subthreshold:

\[ n \text{ or } I_D \]
At larger $V_D$:

$n(x) \downarrow \text{ as } x \to L$.

So, output curves bend down.

When $V_G - V_D = V_{th}$,

$n(x=L) = 0$.

"pinch-off"
when $V_G - V_D = V_{th}$,

$n(x=L) = 0$.

"pinch-off"

when $V_G - V_D > V_{th}$, $I_D$ no longer increases with $V_D$.

"Saturation" regime.

\[ I_D \propto (V_G - V_{th})^2 \]

\[ g_m = \frac{dI_D}{dV_G} = \mu C_{ox} \frac{W}{L} (V_G - V_{th}) \]
Comments on the sub-$V_{th}$ regime.

\[ I \propto e^{\frac{qV_g}{kT}} \]

\[ \xi = 1 + \frac{C_d}{C_{ox}} \]

Best limit: $\xi = 1$

\[ \frac{d}{dV_g} \log I = \frac{1}{60} \text{ dec/mV} \]

-- sub-$V_{th}$ slope.

\[ \frac{dV_g}{d\left(\log I\right)} = 60 \text{ mV/dec} \]

-- sub-$V_{th}$ swing.

It's a hot research area to come up with new devices with swing < 60 mV/dec.
Small-signal equivalent circuit

Saturation regime used in amplifiers

\[ g_m = \frac{\partial I_D}{\partial V_G} = \mu C_{ox} \frac{W}{L} (V_G - V_{th}) \]

Gain = \( g_m R_L \)