Field effect transistors

Remaining material in this course:

Shur, Chapter 4, Sections:
Sect. 4.1-4.5
Sect. 4.7
Sect. 4.9
Sect. 4.11

Shur, Chapter 7, all sections

Required Problems:

4-2-6
4-3-3
4-4-1
4-4-3
4-4-6
4-5-7
4-5-10
4-7-2
4-11-1†
7-3-1

Shall we have a class on November 25 ?

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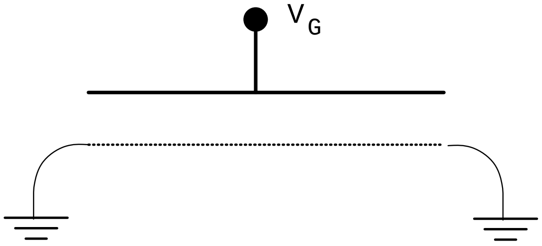
† Note a misprint in the formulation of this problem; it is Eq. (4-11-7) that must be derived, not Eq. (4.11.12).

Two Dimensional Channel



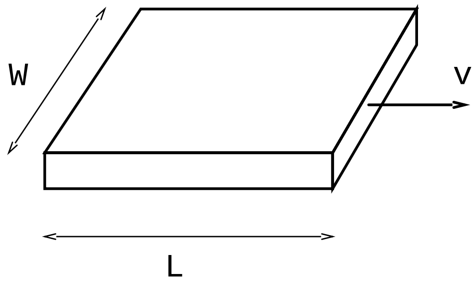
$$e\,n\ [\,\mathrm{cm}^{-2}\,] = \frac{C}{A}\,V_{\mathrm{G}}$$

Conductance of 3D sample:

$$g \equiv \frac{\mathrm{d}I}{\mathrm{d}V} = [\,e\,N\,\mu\,]\,\frac{A}{L}\ , \qquad e\,N\,\mu\ \left[\frac{1}{\Omega\cdot\mathrm{cm}}\right]$$

Conductance of 2D sample:

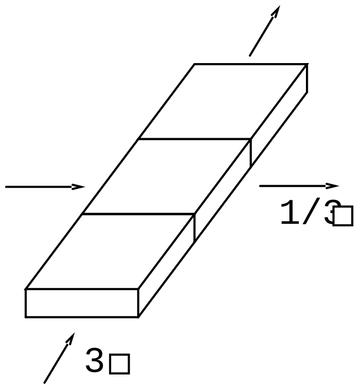
$$g \equiv \frac{\mathrm{d}I}{\mathrm{d}V} = [\,e\,n\,\mu\,]\,\frac{W}{L}\ , \qquad e\,n\,\mu\ \left[\frac{1}{\Omega}\right]$$



Note: resistance of a square independent of its size (contrast with a cube!) ☛ Ω/□

Knowing the "resistance per square" $\frac{1}{e\,n\,\mu}$

one can simply count squares:



Current density per unit width $[\mathrm{A\ cm^{-1}}]$

$$J \equiv \frac{I}{W} = en\,v$$

$$= en\,\mu F = en\,\mu\,\frac{V}{L}$$

conductance per unit channel width ☛ $g = en\,\mu/L \quad [\mathrm{mS/mm}]$

Transconductance (also per unit width)

$$g_{\mathrm{m}} \equiv \left.\frac{\partial J}{\partial V_{\mathrm{G}}}\right]_{V_{\mathrm{D}}}$$

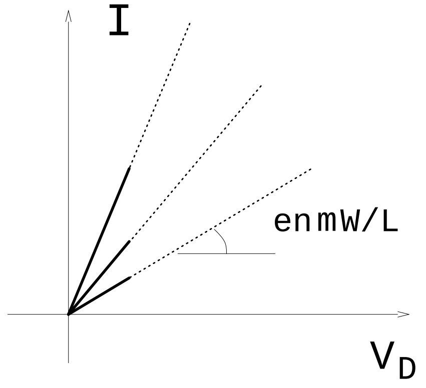
$$J = en\,v$$

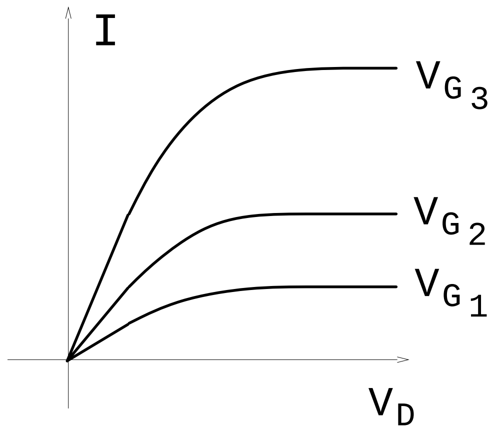
$$g_{\mathrm{m}} = \frac{\partial(en)}{\partial V_{\mathrm{G}}}\,n = \frac{C}{A}\,v \quad [\mathrm{mS/mm}]$$

Figure of Merit ("FOM"):

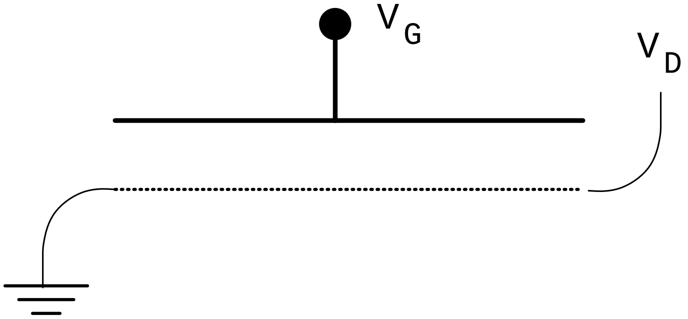
$$\frac{C}{g_{\mathrm{m}}} = \frac{L}{v} \qquad (\text{delay time})$$

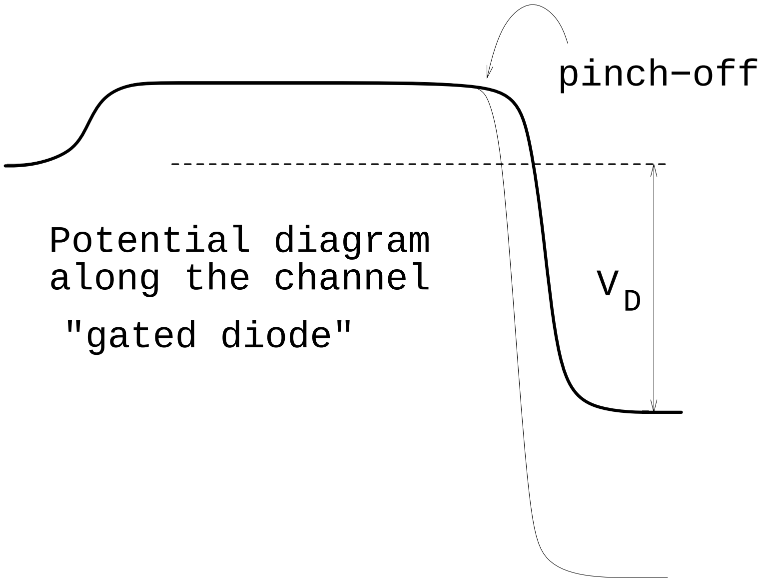
Characteristics





Transistor channel versus thin film diode

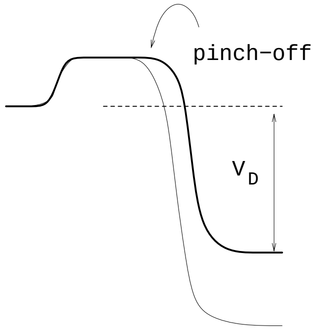




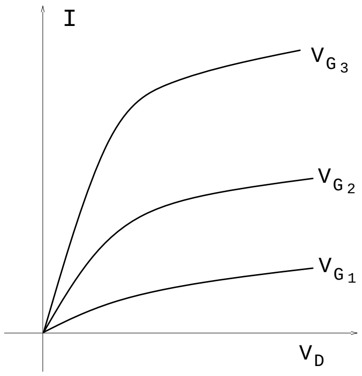
Potential diagram along the channel

"gated diode"

Short channel effects



As the pinch off point moves left, the channel becomes shorter.
The decreasing L leads to increasing current (finite output conductance)
Recall Early effect in bipolars

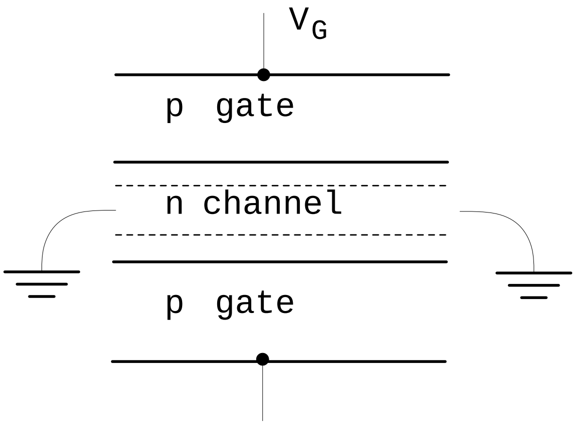


For a given channel length, the closer the gate to the channel, the less important are the short-channel effects

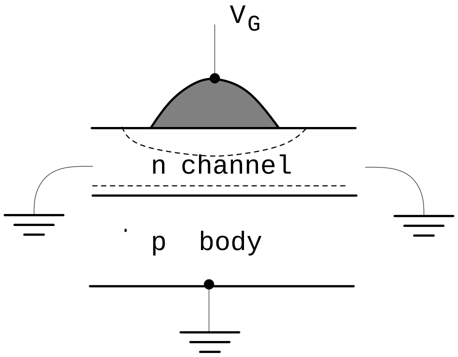
JFET and **MESFET**

Channel is an undepleted portion of a thin layer
Thickness of the undepleted portion is controlled by a gate

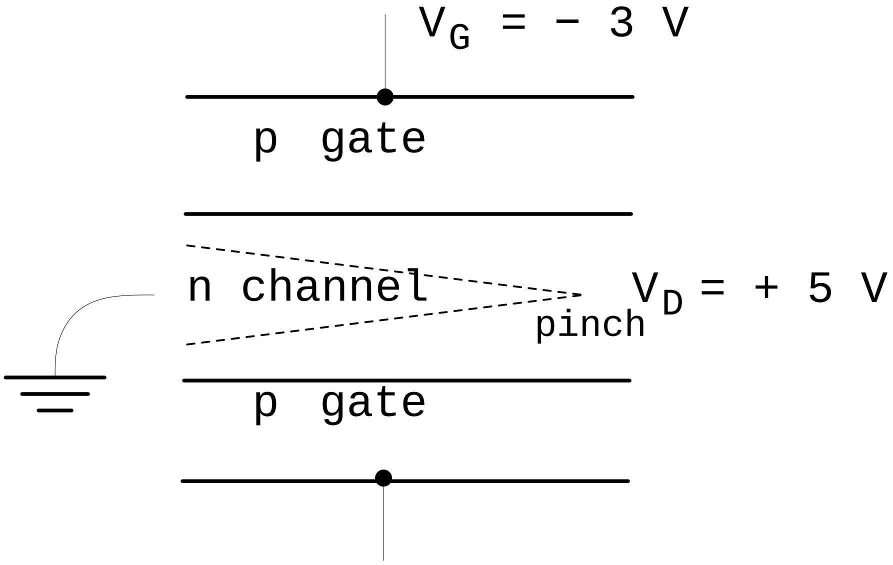
Junction FET



Metal-Semiconductor FET



Pinch off in a JFET



Gradual channel approximation

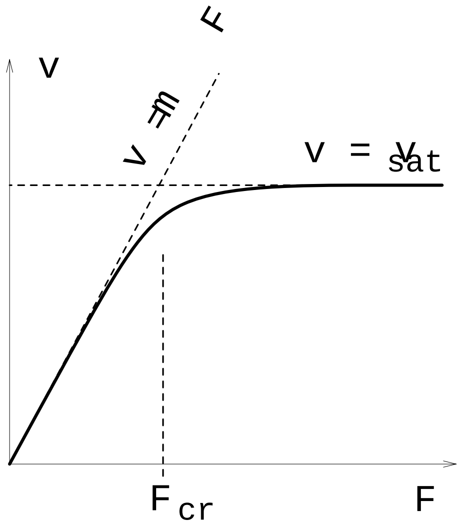
Treat the potential diagram at any channel cross-section (x)
as if there is no current, no voltage difference between the source and the drain, but the channel is not at ground voltage but at $V = V_{\mathrm{ch}}(x)$

This is equivalent to replacing $V_{\mathrm{G}} \to V_{\mathrm{G}} - V_{\mathrm{ch}}(x)$

For a sufficiently high V_{D} the effective value of the gate voltage goes below threshold near the drain and pinch off forms. When that happens, the characteristics saturate because the pinch-off point does not move very much with increasing V_{D} (think why!).

In short channel devices, the small decrease of the effective channel length is still appreciable and characteristics do not saturate.

Velocity-field characteristics



Typical numbers to remember:

$$v_{\text{sat}} \approx 10^{7} \text{ cm/s}$$
$$n \approx 10^{12} \text{ cm}^{-2}$$
$$J = e\, n\, v_{\text{sat}} \approx 1 \text{ A/cm} = 100 \text{ mA/mm}$$

MOS structure

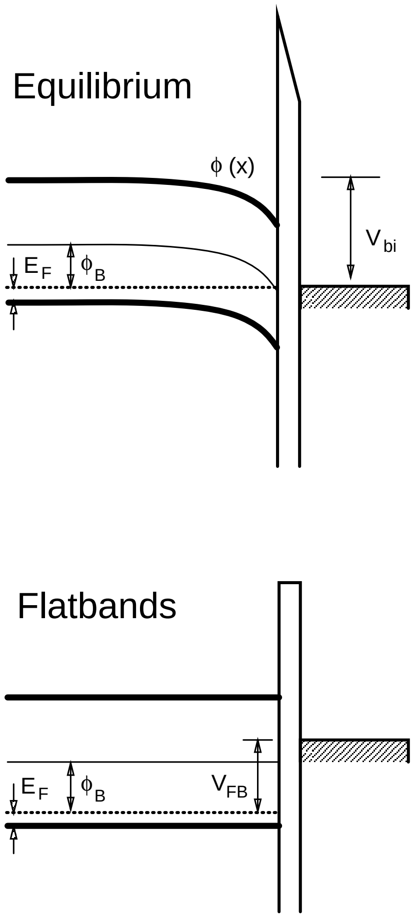


Figure 1: Built-in voltage V_{bi} and flatband voltage V_{FB}.

These quantities are not identical.

V_{bi} is the electrostatic potential drop in equilibrium: it equals sum of the potential drops in the semiconductor and the oxide.

V_{FB} is the voltage that must be applied to the gate to flatten the bands. Since "voltage" means the Fermi level difference,† the V_{FB} equals the difference in the work functions of the semiconductor and the metal.

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† Not the same thing as the electrostatic potential difference, which can exist even in equilibrium.

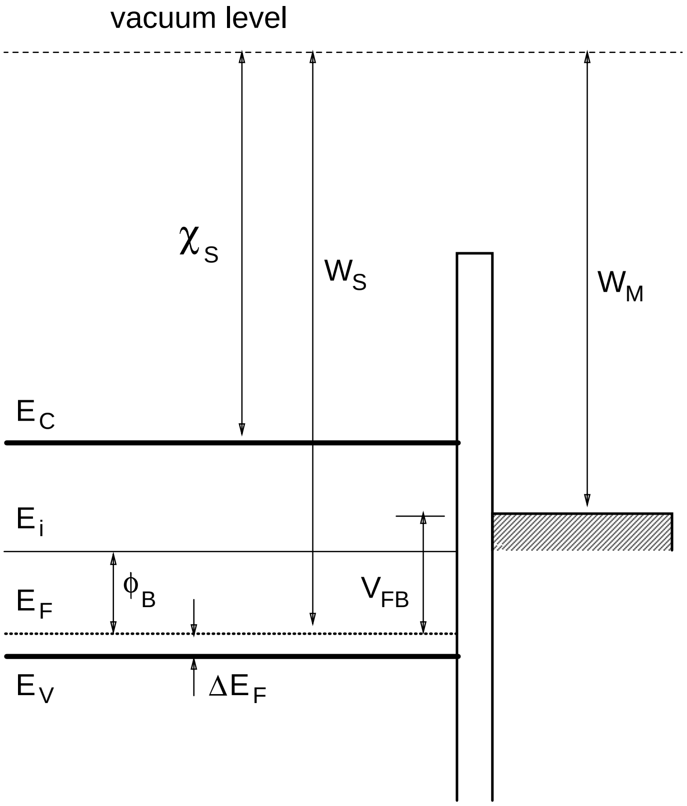

Figure 2: Relevant energies in the MOS system at flatbands.

- W_S: work function of the semiconductor
- W_M: work function of the metal
- $V_{FB} = W_S - W_M$: flatband gate voltage
- χ_S: electron affinity of the semiconductor
- $\phi_B \equiv E_i - E_F$: bulk doping characteristic, $\phi_B = kT \ln(N_A/n_i)$.

$$\begin{aligned} W_S &= \chi_S + E_G - \Delta E_F \\ &= \chi_S + (E_C - E_V) - (E_F - E_V) \\ &= \chi_S + E_C - E_F \end{aligned}$$

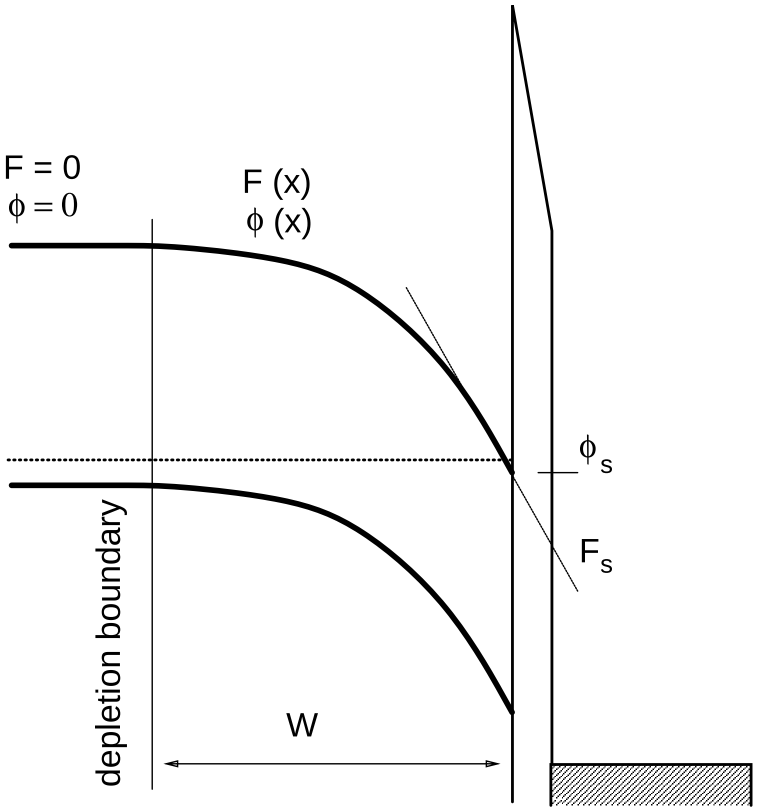

Figure 3: Evaluation of the band bending in MOS structure

Poisson's equation: $$\phi'' = -\frac{e(N_A - p)}{\varepsilon}$$

$p = N_A e^{-\beta\phi}$ ☛ $$\phi'' = -\frac{eN_A}{\varepsilon}\left[1 - e^{-\beta\phi}\right] \qquad (1)$$

Note a trick: $$\phi'' \equiv \frac{d\phi'}{dx} = \frac{d\phi'}{d\phi}\frac{d\phi}{dx} = \frac{dF}{d\phi}F = \frac{1}{2}\frac{dF^2}{d\phi}$$

☛ multiply Poisson's equation (1) by dφ and integrate

from $x = -\infty$ $\phi = 0$ $F = 0$
to $x =$ surface $\phi = \phi_S$ $F = F_S$

using

$$\int_0^{\phi_S}\left[1 - e^{-\beta\phi}\right] d\phi = \frac{kT}{e}\left[\beta\phi_S + e^{-\beta\phi_S} - 1\right]$$

Exact:

$$\frac{1}{2}\,F_S^2 \;=\; \frac{kT\,N_A}{\varepsilon}\left[\beta\phi_S + e^{-\beta\phi_S} - 1\right]$$

Approximate ($\beta\phi_S \gg 1$, i.e., $\phi_S \gg kT/e$):

$$F_S^2 \;=\; \frac{2kT\,N_A}{\varepsilon}\,\beta\phi_S \;=\; \frac{2\,e\,N_A}{\varepsilon}\,\phi_S$$

The same result is obtained in the depletion approximation:

$$\phi_S \;=\; \frac{eN_A\,W^2}{2\,\varepsilon} \qquad\qquad F_S \;=\; \frac{eN_A\,W}{\varepsilon}$$ where W is the depletion width

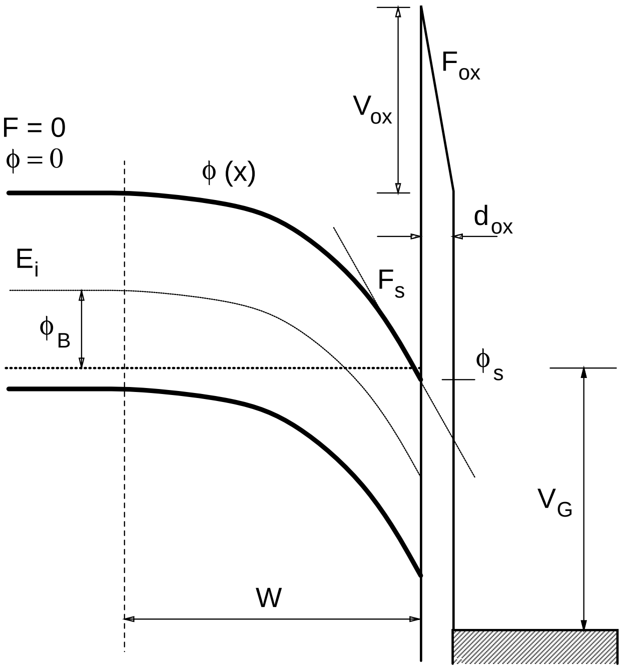

Figure 4: Threshold gate voltage evaluation:

Given bulk doping N_A	☞	$e\phi_B = kT\,\ln(N_A/n_i)$
at threshold $\phi_S = 2\,\phi_B$	☞	$F_S = \sqrt{\dfrac{4e\,N_A\,\phi_B}{\varepsilon_S}}$
$\varepsilon_S F_S \;=\; \varepsilon_{OX} F_{OX}$	☞	$F_{OX} = \dfrac{\varepsilon_S}{\varepsilon_{OX}}\sqrt{\dfrac{4e\,N_A\,\phi_B}{\varepsilon_S}}$
$V_{OX} \equiv d_{OX} F_{OX}$	☞	$V_T \;=\; e\,\phi_S \;+\; V_{OX} \;+\; V_{FB}$

Pinch off in a MOSFET

Recall the gradual channel approximation: Treat the potential diagram ***locally*** at any channel cross-section (x) by ignoring the voltage difference between the source and the drain, but taking the channel to be not not at ground voltage but at $V = V_{\mathrm{ch}}(x)$, i.e., by replacing

☛ $V_{\mathrm{G}} \rightarrow V_{\mathrm{G}} - V_{\mathrm{ch}}(x)$

The $V_{\mathrm{ch}}(x)$ is the imref (the quasi-Fermi level) which varies monotonically from $E_{\mathrm{F}} = 0$ in the source to $E_{\mathrm{F}} = V_{\mathrm{D}}$ in the drain.