Field-effect transistors (FETs)

Field-effect transistors are basically variable resistors, where the resistance is controlled by a third terminal called a gate.

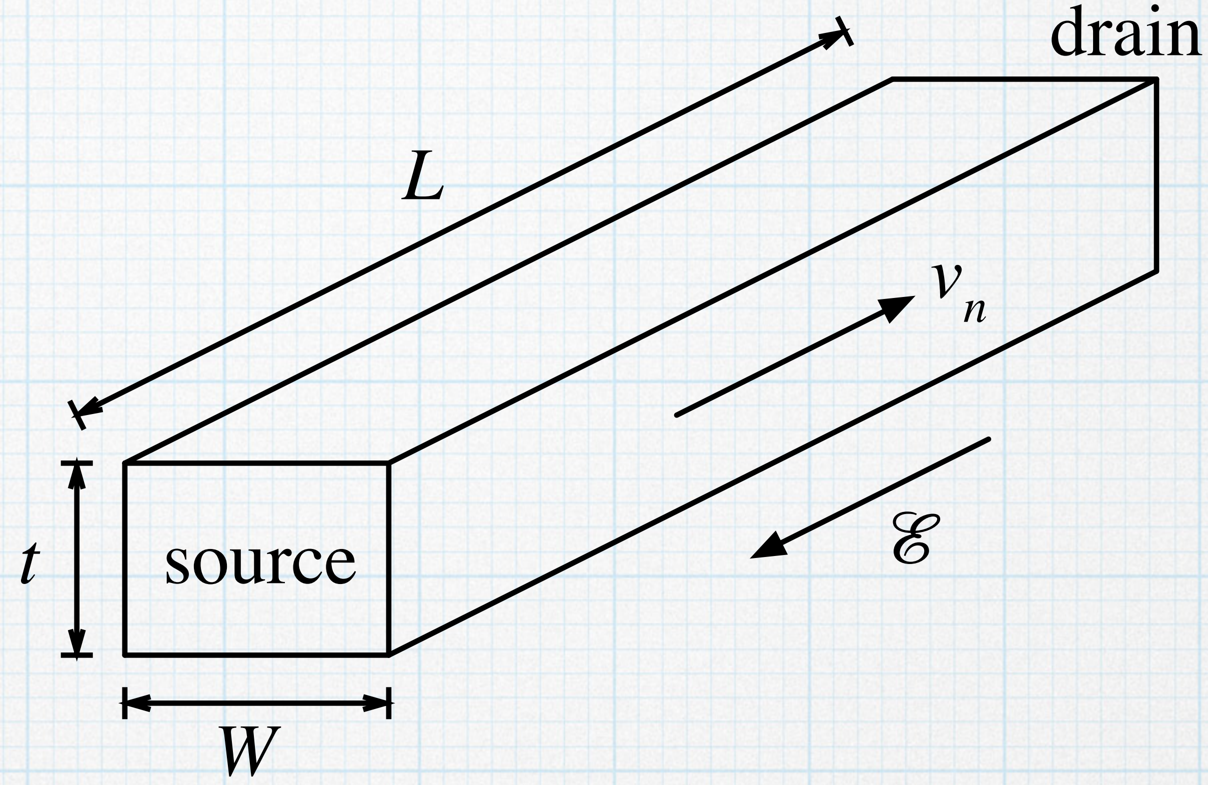
- Proposed long before BJTs (1920s by Lilienfield), but not realized until well after BJTs. FETs became dominant in 1980s.
- Carriers enter the FET at the source and exit at the drain. The path from source to drain is called the channel.
- There is no DC current flowing in or out of the gate, so source current equals drain current. (Always referred to as drain current.)
- As a first cut, the carriers move by drift with one type of carrier being dominant, so FETs are considered to be *unipolar* devices.
- If current is carried by electrons, the FET is an *n*-channel device and the current flows from drain to source.
- If the current is carried by holes, it is a *p*-channel device and the current flows from source to drain.

FETs

Different FETs are distinguished by the mechanism through which the gate controls the drain current.

- Junction FETs (JFETs) and Metal-semiconductor FETs (MESFETs) use reverse-biased pn junctions to "squeeze" the width of a channel. The gate voltage adjusts the depletion-layer widths and hence the effective width of the channel. These were the first FETs, but are virtually obsolete now.
- Heterojunction and quantum-well FETs (HFETs, QWFETs) use carefully constructed semiconductor layers to confine a carriers in a narrow channel (band-gap engineering). The applied gate voltage moves the bands up and down, adjusting the number of carriers in the channel. Generally, these heterojunction-based devices used semiconductors that have t high electron mobilities, and so they also known as high-electron mobility transistors (HEMTs)
- Metal oxide semiconductor FETs (MOSFETs) use an insulating layer (usually silicon dioxide) to create a thin layer of electrons or holes (inversion layer). The gate couples to the channel carriers using the capacitance formed by the insulator.

Recall the simple resistor:



$$J_n = qnv_n$$

$$v_n = \mu_n \mathscr{E}$$

$$J_n = qn\mu_n \mathscr{E}$$

If n is uniform down the length of the resistor, $n = N_D$ and

$$\mathscr{E} = \frac{V_{DS}}{L}$$

$$I_D = J_n (W \cdot t)$$

$$I_D = q\mu_n \left(N_D t\right) \left(\frac{W}{L}\right) V_{DS}$$

We will find it useful to combine the carrier concentration and the thickness of the conducting channel into a single quantity called the sheet concentration, n_s:

$$n_s = n \cdot t$$

The units are m^{-2} (cm^{-2} or μm^{-2})

$$I_D = q\mu_n n_s \left(\frac{W}{L}\right) V_{DS} \qquad\qquad R_{DS} = \frac{1}{q\mu_n n_s \left(\frac{W}{L}\right)}$$

One of the things that we will see almost immediately is that the concentration is not uniform down the length of the channel. The non-uniformity is caused by the combination of the gate voltage controlling the sheet concentration in the channel and the drain voltage that causes the carriers to flow along the channel.

FETs are inherently two-dimensional devices — there are field along the channel (moving carriers) and transverse to the channel (controlling concentrations). We will try to hide the two-dimensional nature, but ultimately we will not be completely successful.

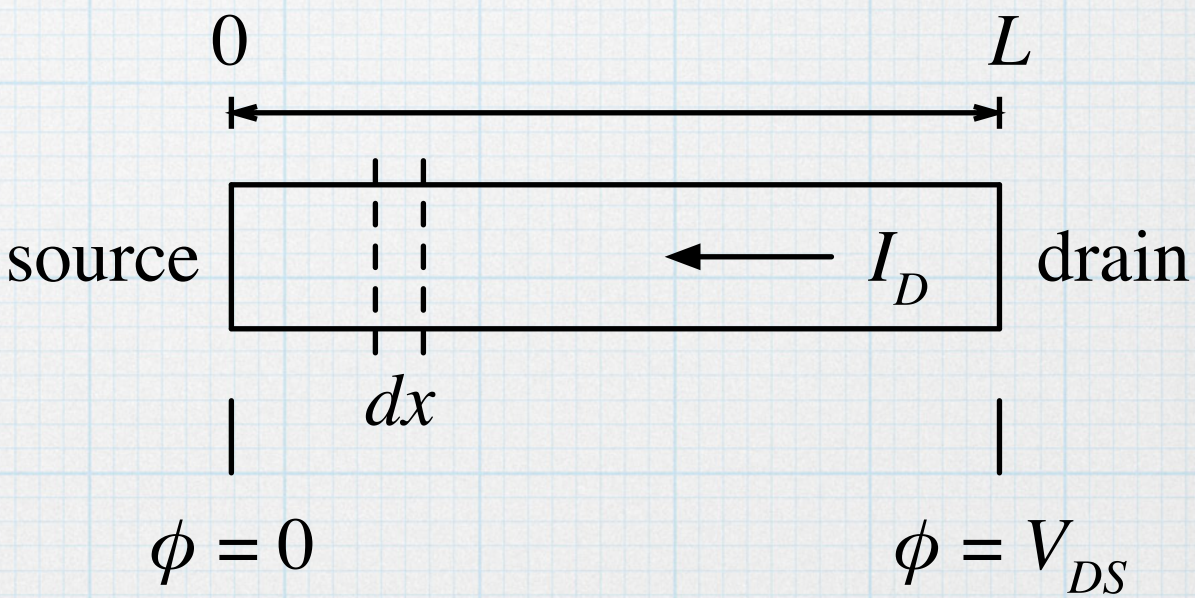
If carrier concentration is not constant down the length of the channel, then we cannot define a simple channel resistance.

Recall that the current at each point along the channel must be continuous. (KCL) At any point x along the channel,

$$I_D = qW\mu_n(x)\, n_s(x)\, \frac{d\phi}{dx}$$

The variations along the channel (in the x-direction) are caused by variations in the electrostatic potential. So μ_n and n_s are implicit functions of ϕ.

$$I_D = qW\mu_n(\phi)\, n_s(\phi)\, \frac{d\phi}{dx}$$



$$I_D dx = qW\mu_n(\phi)\, n_s(\phi)\, d\phi$$

$$\int_0^L I_D dx = \int_0^{V_{DS}} qW\mu_n(\phi)\, n_s(\phi)\, d\phi$$

$$I_D = \frac{qW}{L}\int_0^{V_{DS}} \mu_n(\phi)\, n_s(\phi)\, d\phi$$

$$I_D = \frac{qW}{L} \int_0^{V_{DS}} \mu_n(\phi)\, n_s(\phi)\, d\phi$$

So for a given type of FET, we need to determine how ns depends on the local electrostatic potential. (Presumably, that will also allow us to determine how the mobility varies, as well.) From electromagnetics, we know about Poisson's equation:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = -\frac{\rho(x, y)}{\epsilon}$$

Yikes! Here is the two-dimensionality staring us in the face. This will be hard. To make it easier, we will often start by invoking the *gradual-channel approximation*, in which we assume that the variations along the channel (in the x-direction) are much weaker than the variations across the channel (in the y-direction).

$$\frac{\partial \phi}{\partial x} << \frac{\partial \phi}{\partial y}$$

(Stated another way: the electric field along the channel is weaker than the field across the channel.)

$$\frac{\partial^2 \phi}{\partial y^2} = -\frac{\rho}{\epsilon}$$

This will be easier to solve.