# 3.15
# Transistors
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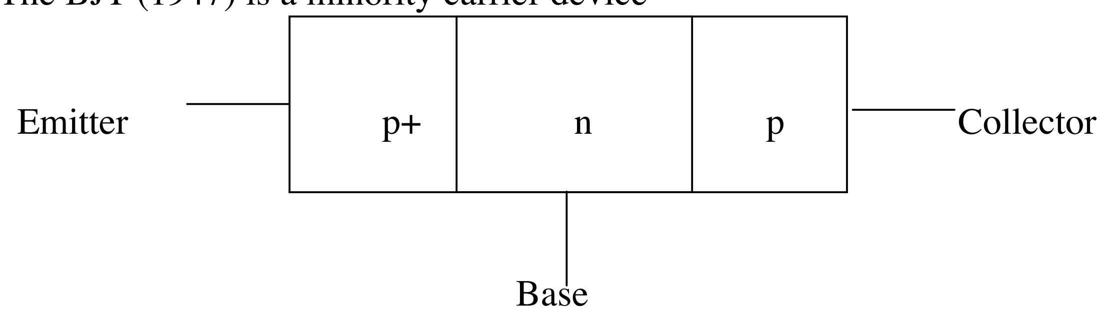
Reference: Pierret, chapter 10, 15.1-2, 16.1-2 and 17.1.

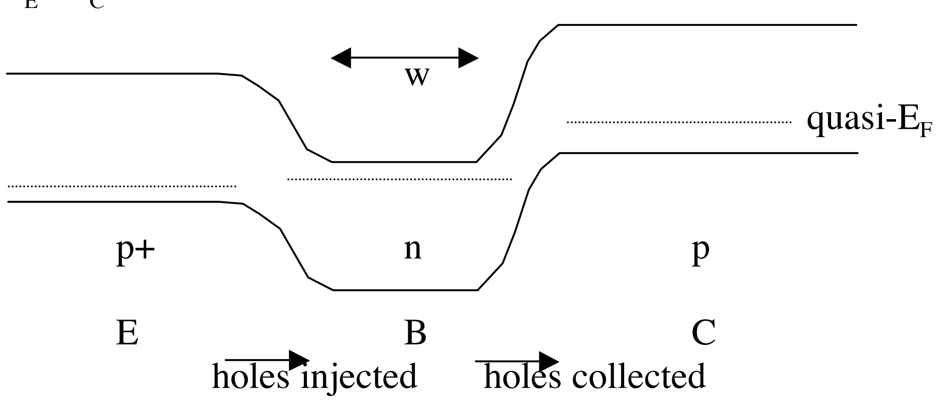
Transistors are three-terminal devices that use a small voltage (or current) applied to one contact to modulate (i.e. control) a large voltage (or current) between the other two contacts.
An analogy is the vacuum tube from the 1900s. A small voltage applied to the 'grid' modulates a large current between the anode and cathode.

**<u>The bipolar junction transistor</u>**
The BJT (1947) is a minority carrier device




Four modes (forward active, reverse active, saturation, cutoff)

<u>Forward active operation</u> (pnp transistor)
The emitter E emits minority carriers into the base B: EB is forward biased
Holes survive their journey through the base
The collector C collects minority carriers from the base B: BC is reverse biased.
A small voltage (or current) at B has a large effect on the current $I_E$
$I_B << I_E \sim I_C$



Forward current $I_E$
At the edge of the depletion region at the left of the base,

$$p = (n_i^2/N_{D,B}) \exp(eV_{EB}/kT)$$

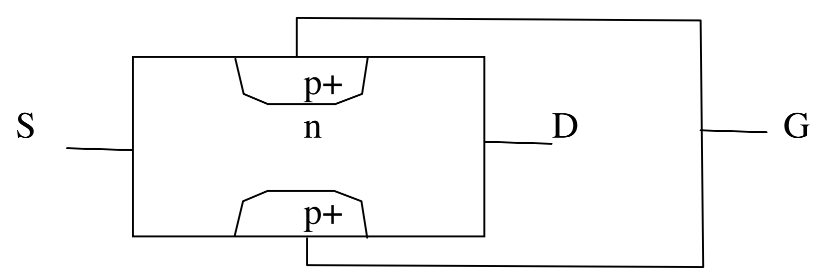
At the right of the base, $p = 0$
Current across base $I_E = (eD_p/w)\,(n_i^2/N_{D,B}) \exp(eV_{EB}/kT)$

Base current $I_B$
The base current << collector current, so most current goes straight through from E to C.
Current gain $\alpha = I_C / I_E \sim 1$, $\beta = I_C / I_B \sim 100 - 1000$
$I_B =$ $I_n$ (electrons going from B to E in forward bias)
 $+ I_{nC}$ (electrons going from C to B in reverse bias -small)
 $+ eR_B$ (recombination in base -small)
The gain $\beta = I_C / I_B \sim I_E / I_B = N_{A,E} / N_{D,B}$ is determined by doping.

'Common base' circuit: by setting $V_{EB}$ and $I_E$ we control $V_{CB}$ and $I_C$
'Common emitter' circuit: by setting $V_{EB}$ and $I_B$ we control $V_{EC}$ and $I_C$
Digital logic: make the transistor act like a switch by running between saturation and cutoff.

**Junction Field Effect Transistor**

Apply a reverse voltage to gate G. This makes the depletion regions grow, alters the n-channel width and therefore alters its resistance, which changes the source-drain voltage (for constant current). This is a voltage amplifier and also a majority carrier device.

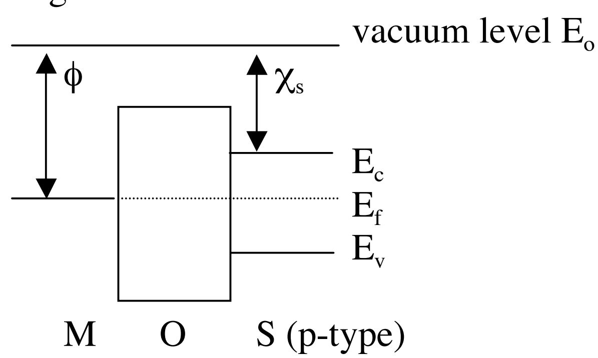



For $V_G = 0$ it is a linear resistor. However, applying $V_{SD}$ causes pinch-off (i.e. the depletion regions touch) and no more current $I_{SD}$ can flow.
Applying a negative $V_G$ makes pinchoff occur earlier.
Beyond pinchoff, a small change in $V_G$ causes a large change in $V_{SD}$.

For depletion width d, channel length t, and initial channel width t, at pinchoff, $V_{SD,\, sat} = (eN_D t^2/8\varepsilon_o\varepsilon_r) - (V_o + V_G)$

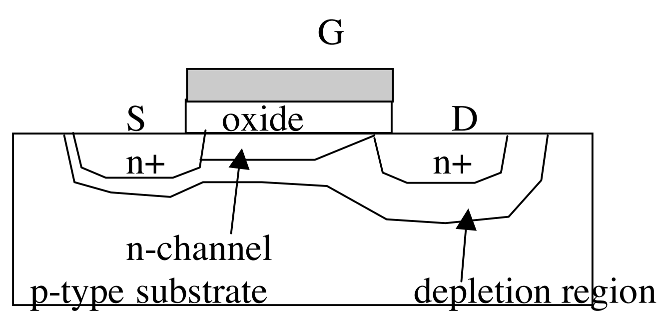
**<u>MOS devices (metal – oxide – semiconductor)</u>**

Ideal MOS bandstructure: where $\phi = \chi_s + (E_c - E_f)$, the Fermi level is flat without any band bending




Negative voltage to the gate (i.e. to the metal) causes charge to accumulate (acts as a capacitor)
Small positive voltage to the gate causes charge to be depleted
Large positive voltage to the gate causes inversion: once all the mobile carriers are depleted, carriers of the opposite sign are attracted to the region of the semiconductor next to the oxide. This creates a channel of opposite type.

<u>MOSFET</u>




Source and substrate are grounded. Applying a large positive $V_G$ creates an n-channel which conducts current between S and D.
If $V_D = 0$, channel has uniform width.
If $V_D > 0$, channel is thinner towards the D and may pinch-off; also the depletion width is larger.
At pinch-off, the current $I_{SD}$ cannot increase any more.
Example application: a DRAM (dynamic random access memory) stores one bit in a cell consisting of a MOSFET plus a MOS-capacitor. Opening the channel of the MOSFET (by applying $V_G$) allows the capacitor to be charged to represent '1' or uncharged for '0'.

**Cross section of a MOSFET.** This high resolution transmission electron micrograph of a silicon Metal-Oxide-Semiconductor Field Effect Transistor shows the silicon channel and metal gate separated by a thin (40Å, 4nm) silicon-dioxide insulator. The inset shows a magnified view of the three regions, in which individual rows of atoms in the crystalline silicon can be distinguished. (Photograph courtesy of AT&T Bell Laboratories.)