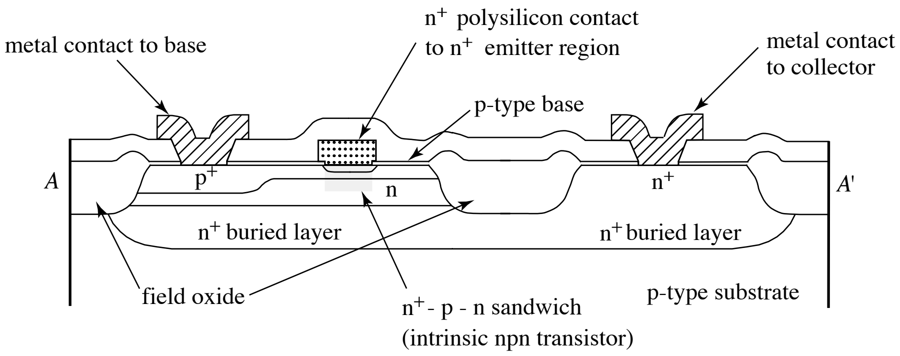
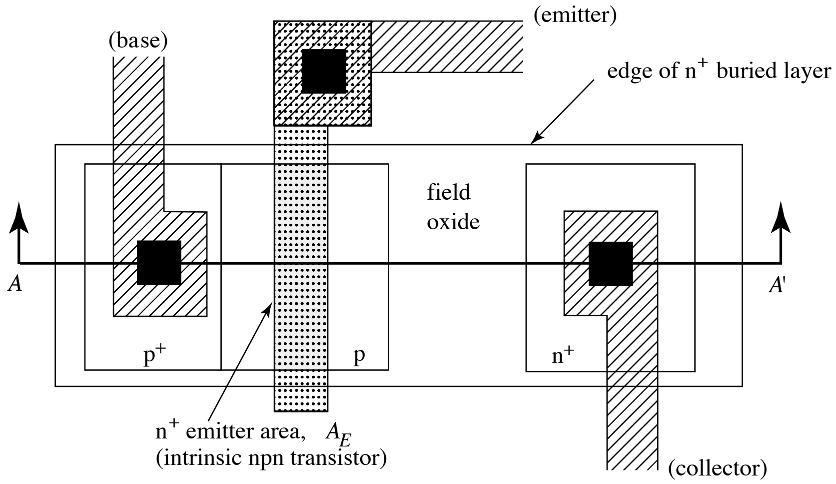
The Bipolar Junction Transistor

- Physical Structure: oxide-isolated, low-voltage, high-frequency design ... typical of the bipolar transistor found in a BiCMOS process, such as the MicroLinear tile array chips used in the laboratory experiments



(a)

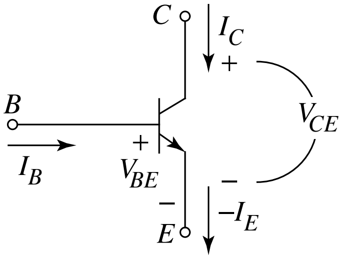


(b)

Circuit Symbol and Terminal Characteristics

- As with MOSFETs, we have two devices that have complementary characterisitcs, in this case the npn transistor and the pnp transistor

  The direction of the diode arrow indicates whether the central layer (the base) is n or p



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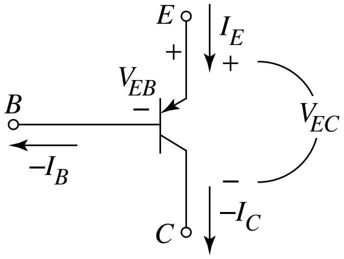


(b)

npn

normal operation:

I_C positive
I_B positive
$-I_E$ positive

V_{CE} positive
$V_{BE} = 0.7$ V

pnp

normal operation:

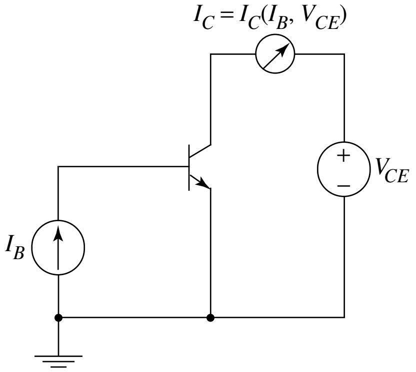
$-I_C$ positive
$-I_B$ positive
I_E positive

V_{EC} positive
$V_{EB} = 0.7$ V

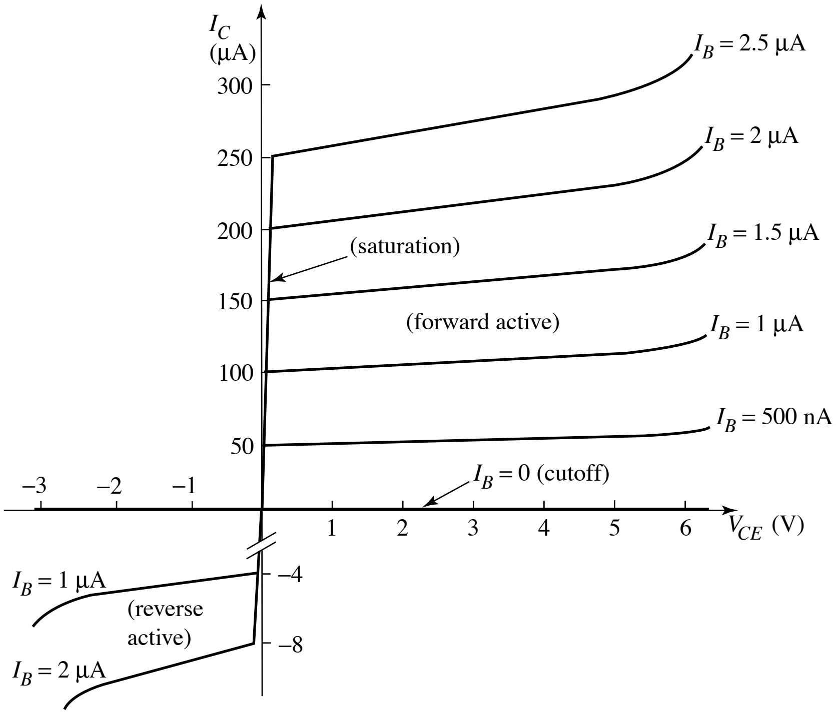
- The pnp usually has a very different physical structure ... we will concentrate on the npn and then consider the pnp briefly

npn BJT Collector Characteristics

- Similar test circuit as for n-channel MOSFET ... except I_B is controlled instead of V_{BE} (for convenience)



(a)



(b)

Regions of Operation

- Constant-current region is called *forward active* ... corresponds to MOSFET saturation region (!?!)

$$I_C = \beta_F I_B$$

- Constant-voltage region is called *saturation* ... corresponds to MOSFET triode region

$$V_{CE} \approx V_{CE(sat)} = 0.1V \text{ or } 0.2\text{ V}$$

- *Cutoff* ... corresponds to MOSFET cutoff region
- *Reverse active* ... terminal voltages for npn sandwich are flipped so that V_{CE} is negative and $V_{BC} = 0.7$ V. Only occasionally useful.

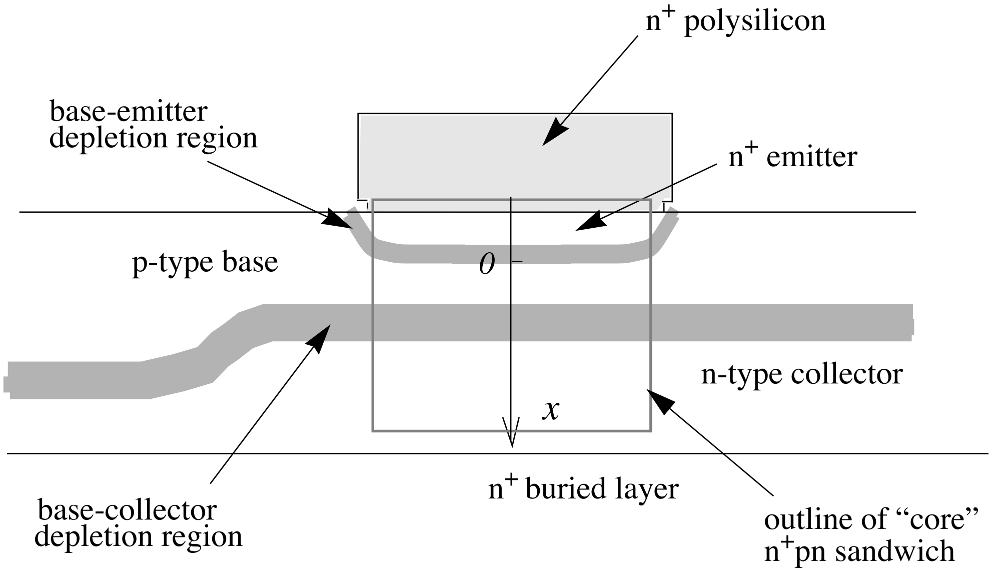
Boundary between saturation and forward-active regions:

$$V_{CE} > V_{CE(sat)} \qquad \text{and} \qquad I_B > 0$$

... much easier to apply this test than $V_{DS} > V_{DS(sat)}$

Bipolar Transistor Physics

- Build on our understanding of the short-base diode; focus initially on the *forward active* region.

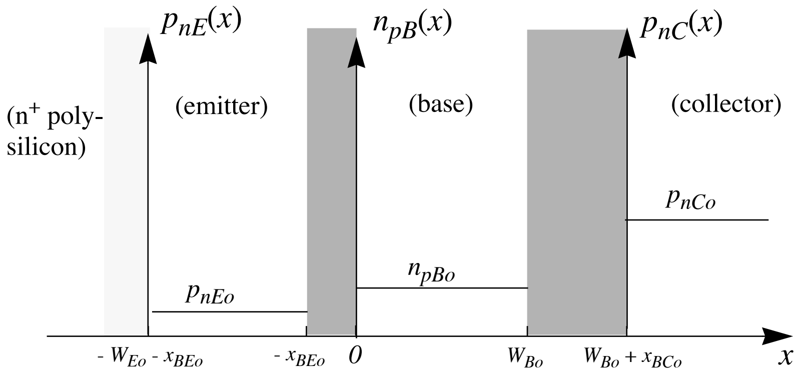


- Procedure:

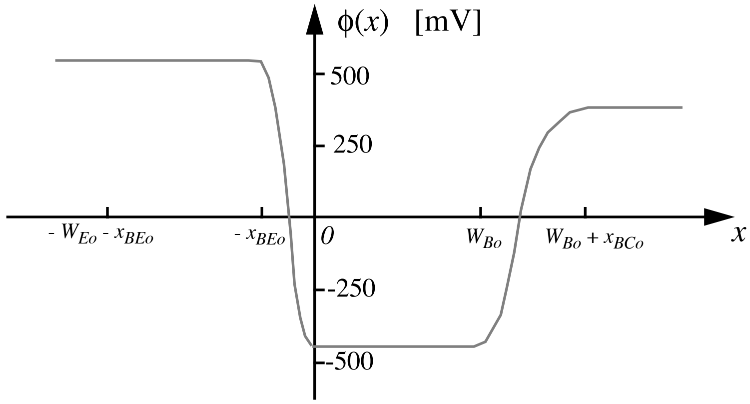
1. understand thermal equilibrium potential and carrier concentrations.
2. apply the Law of the Junction with $V_{BE} = 0.7$ V and $V_{BC} < 0$ (typical forward-active bias point) to find the minority carrier concentrations at the depletion region edges.
3. assume that the emitter and the base regions are "short" and find the diffusion currents.
4. figure out where the drift currents fit in to complete the picture.

Thermal Equilibrium

- emitter is doped two orders of magnitude (at least) more heavily than the base; the collector is an order of magnitude more lightly doped than the base.
- minority carrier concentrations:



- electrostatic potential:



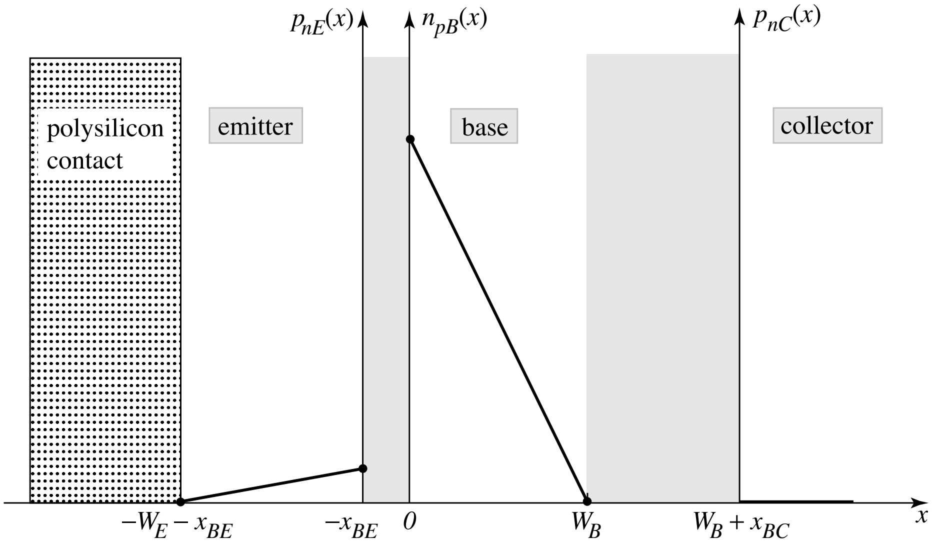
Carrier Concentrations under Forward Active Bias

- The law of the junction gives the boundary conditions on both sides of the base:

  Emitter-Base side of base: $\exp[V_{BE} / V_{th}] >> 0$

  Base-Collector side of base : $\exp[V_{BC} / V_{th}] = 0$ (or very close to it)

- Short Base solution for both the n$^+$ emitter and for the p-type base



Note that the scale is changed from thermal equilibrium and so p_{nCo} is indistinguishable from zero in this plot

The Flux Picture

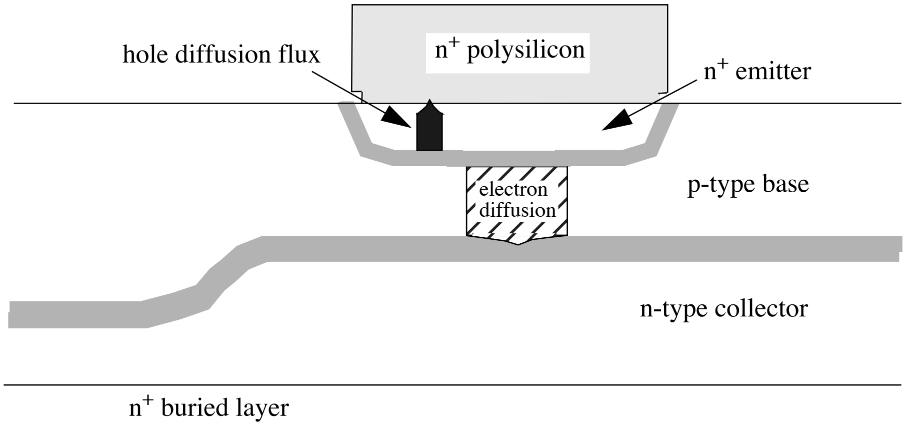
- Rather than current densities, it is more helpful to follow the direction of carrier transport ... so we introduce the concept of

  flux [# per cm^2 per second] ... symbol F

$$F_n = \frac{J_n}{-q} \text{ for electrons}$$

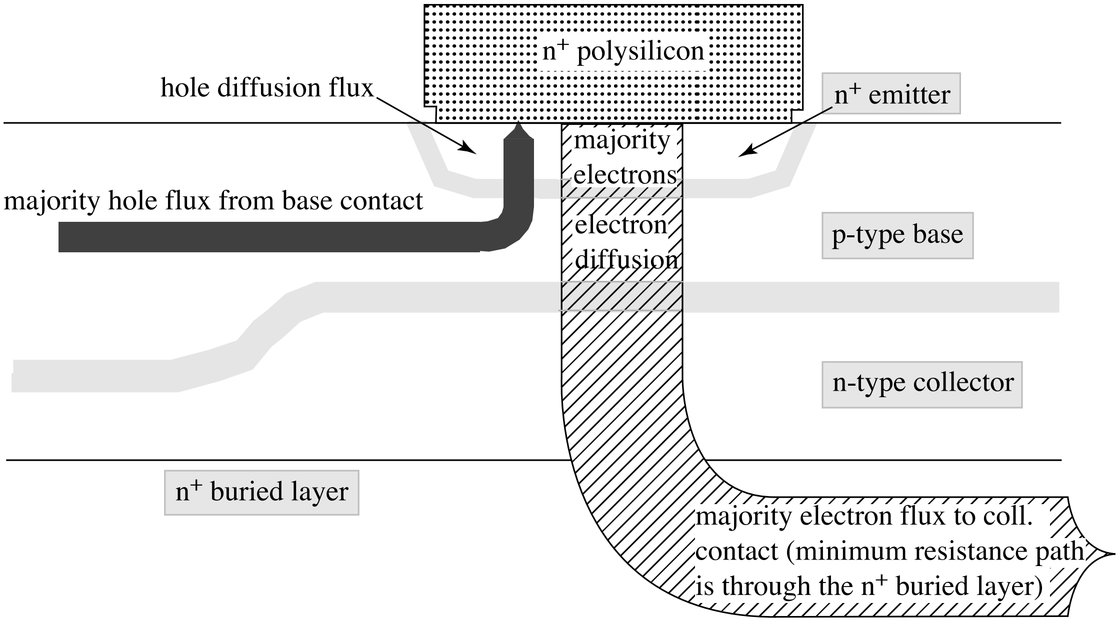
$$F_p = \frac{J_p}{q} \text{ for holes}$$

- The flux of electrons in the base is from *emitter* to *collector*; the flux of holes in the emitter is from the base to the polysilicon contact. The width of the electron flux “stream” is greater than the hole flux stream.



Forward-Active Carrier Flux

- The electrons diffuse across the base, where they reach the base-collector depletion region
- Electric field in the base-collector depletion region points in the - *x* direction, so the force on the electrons is in the + *x* direction and they are swept into the collector (i.e., the collector is well named)
- The n^+ polysilicon/emitter ohmic contact “swallows” the reverse injected holes that reach it and supplies a drift flux of electrons for injection into the base



(b)

Note that the n^+ buried layer provides a low resistance path to the collector contact and that the holes must be supplied from the base contact