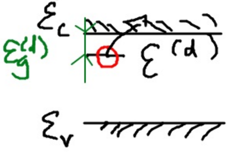
Solid State Physics p-n junctions

intrinsic semiconductor: $\varepsilon_F = \frac{1}{2}(\varepsilon_v + \varepsilon_c) + \frac{3}{4} k_B T \ln \frac{m_h}{m_c}$

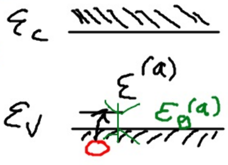
doped (added a small portion of $\underbrace{\text{other atoms}}_{\text{dopants}}$) ⇒ extrinsic semiconductor



$k_B T \doteq 0.0258\ eV$

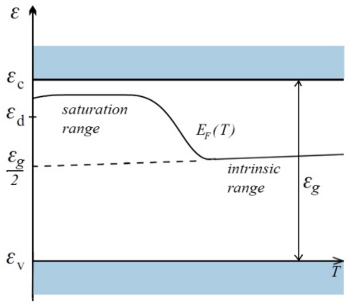
impurities

$\varepsilon_c - \varepsilon^{(d)} \sim 0.001\ eV$



$\varepsilon^{(a)} - \varepsilon_v \sim 0.001\ eV$

$$\left.\begin{matrix}\Delta \varepsilon_g^{(d)} \\ \Delta \varepsilon_g^{(a)}\end{matrix}\right\} < 3 k_B T \Longrightarrow \text{extrinsic semic. are degenerate}$$



$$\varepsilon_F^{(d)} = \frac{1}{2}(\varepsilon_c + \varepsilon^{(d)}) + \frac{3}{4} k_B T \ln \frac{m_h^*}{m_c}$$

$$\varepsilon_F^{(a)} = \frac{1}{2}(\varepsilon_v + \varepsilon^{(a)}) + \frac{3}{4} k_B T \ln \frac{m_h^*}{m_c}$$

$$n_c^{(d)} = N_c\, e^{-(\varepsilon_c - \varepsilon_F^{(d)})/k_B T}$$

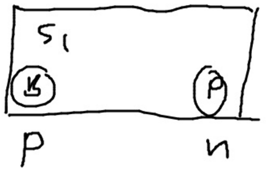
$$p_v^{(a)} = P_v\, e^{-(\varepsilon_F^{(a)} - \varepsilon_v)/k_B T}$$

$$n_i = N_c\, e^{-(\varepsilon_c - \varepsilon_F)/k_B T}$$

$$p_i = P_v\, e^{-(\varepsilon_F - \varepsilon_v)/k_B T}$$

$$n_c^{(d)} = n_i\, e^{-(\varepsilon_F^{(d)} - \varepsilon_F)/k_B T}$$

$$p_v^{(a)} = p_c\, e^{-(\varepsilon_F - \varepsilon_F^{(a)})/k_B T}$$



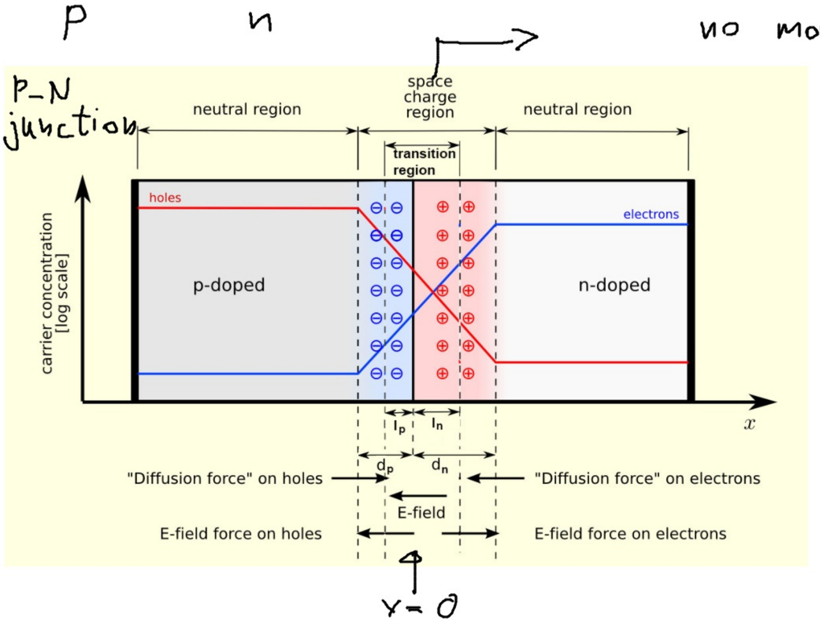
How to dope?

E.g. ion implantation then annealing

no movable charge carriers

⇓ so called

depletion region



creates an electric potential $\varphi(\vec{r})$, which is the solution of Poisson's equation:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = -\frac{\overset{\text{charge density}}{\rho(\vec{r})}}{\epsilon}$$

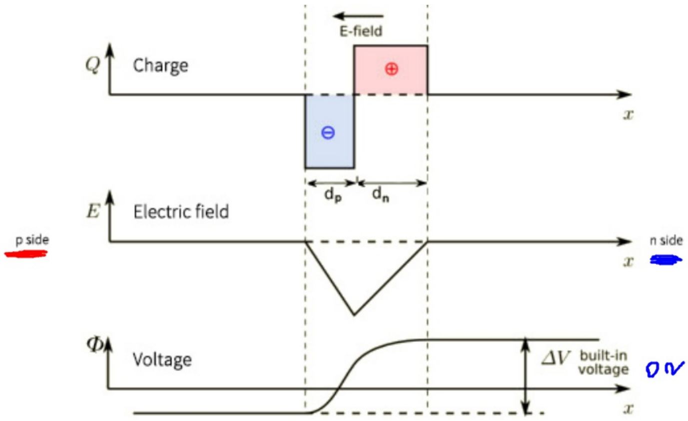
$\epsilon = \epsilon_0 \cdot \epsilon_r$

$$1D \Rightarrow \frac{d^2\varphi}{d^2x} = -\frac{\rho(x)}{\epsilon} \qquad \rho(x) = e\left(N_d(x) - N_a(x) + p_v(x) - n_c(x)\right)$$

$$\rho(x) = \begin{cases} 0 & x < -d_p \\ eN_a & -d_p < x < 0 \\ -eN_d & 0 < x < d_a \\ 0 & d_n < x \end{cases}$$

$$d_p = \sqrt{\frac{N_d}{N_a(N_a+N_d)}\,\epsilon\,\frac{\varphi_0}{2e}} \qquad d_n = \sqrt{\frac{N_a}{N_d(N_a+N_d)}\,\epsilon\,\frac{\varphi_0}{2e}}$$

The un-biased ($V_{ext}=0$) p-n junction



$$n_c \cdot p_v = n_i^2$$

space-charge creates a

or Built-in potential $\Delta\varphi_0$

$$\Delta\varphi_0 = \varphi(\infty) - \varphi(-\infty)$$

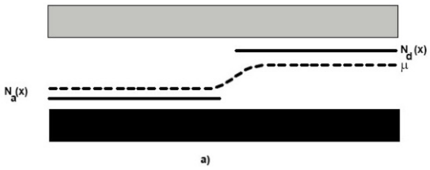
$$e\Delta\varphi_0 = k_BT \ln\frac{N_dN_a}{n_i^2}$$

$$n_c(T,x) = N_c(T)\,e^{-(\mathcal{E}_c - \mathcal{E}_F(x))/k_BT}$$

$$p_v(T,x) = P_v(T)\,e^{-(\mathcal{E}_F(x) - \mathcal{E}_v)/k_BT}$$

$\mathcal{E}_F$ (or μ-chem. pot.) is a function of x $\qquad \mu(x) = \mathcal{E}_F(x)$

Two different views of the same thing



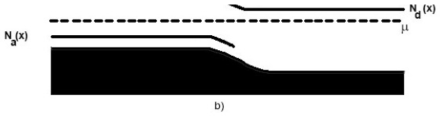
$\mu = \mu(x)$, bands are straight

$\mathcal{E}_v, \mathcal{E}_c$ constant

(does not depend on x)

or

$\mathcal{E}_F$ const. The bands bend!



ε_F const ⇒ bands bend

$\varepsilon_C(x)$

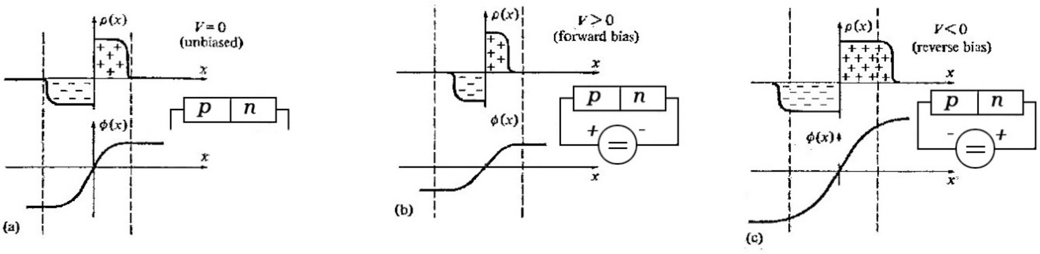
$\varepsilon_F = \mu$ const

$\varepsilon_V(x)$

Biased p-n junctions $V_{ext} \neq 0$, $\underline{E}_{ext} \neq 0$

means $V_{ext} \neq 0$

$$V = \Delta\varphi_0 - V_{ext}$$



$V=0$ $V>0$ $V<0$

just consider the holes for the moment

Two types of current:

1) holes from p-side move through the depletion region to the n-side where they recombine w electrons

$j_h^{(rec)}$ recombination current

depends on V (or V_{ext})

$$j_h^{(rec)}(V) = C \cdot e^{-e\Delta\varphi/k_BT} \qquad \Delta\varepsilon = e\Delta\varphi$$

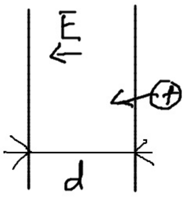
$$\Delta\varphi = \Delta\varphi_0 - V_{ext} \Rightarrow \quad j^{(rec)}(V) = C\, e^{-e\Delta\varphi_0/k_BT} \cdot e^{eV_{ext}/k_BT}$$

2) holes generated on n-side (!) near the depl. region will move to the p-side ($\underline{E}$ is from n → p)

$j_h^{(gen)}$ generation current

independent of V (or V_{ext})

why?



hole generated at the n-side if wander into the depletion region is swept to the p-side by $\underline{E}$

$\Rightarrow j_h^{gen}$ independent of V

$$E = -\frac{\Delta\varphi}{d}$$

10-1000 nm

v_h $\sim 10^5$ m/s $\quad \langle v_h \rangle = v_h^{drift}$ 10^{-3} m/s $\quad$ generation j_h

$j_h^{(gen)} = ?$

• in equilibrium when $V_{ext}=0$

$$j_h^{(gen)} + j_h^{(rec)} = 0$$

$$j_h^{(gen)} = -j_h^{(rec)}(V_{ext}=0) = -C\, e^{-e\Delta\varphi_0/k_BT}$$

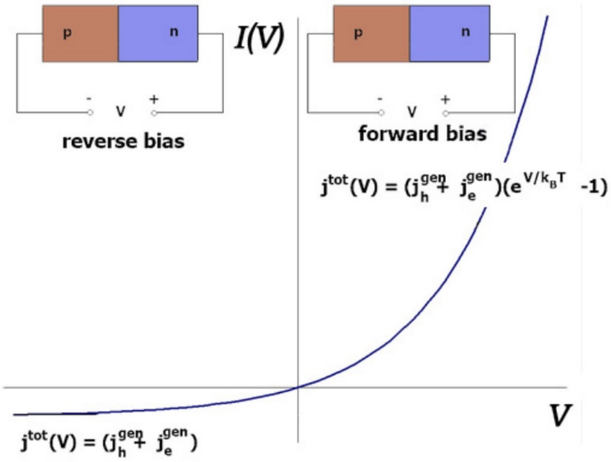
The total current of holes:

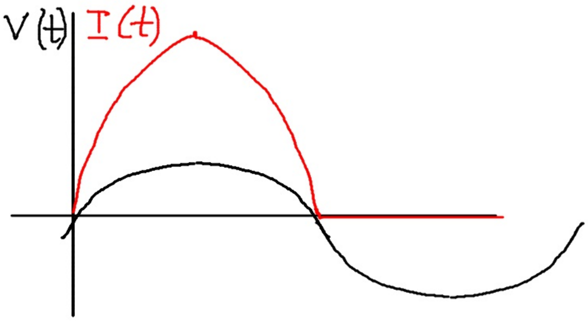
$$j_{tot} = j^{(gen)} + j^{(rec)} = j^{(gen)} + \underbrace{C\, e^{-e\Delta\varphi_0/k_BT}}_{= -j^{(gen)}} \cdot e^{eV_{ext}/k_BT}$$

$$j_{tot}^{(h)} = j_h^{(gen)}\left(e^{eV_{ext}/k_BT} - 1\right)$$

Same for electrons $j_{tot} = j_{tot}^{(h)} + j_{tot}^{(e)} = \underbrace{\left(j_h^{(gen)} + j_e^{(gen)}\right)}_{const}\left(e^{eV_{ext}/k_BT} - 1\right)$

forward bias: $V_{ext} > 0$
reverse -||- : $V_{ext} < 0$

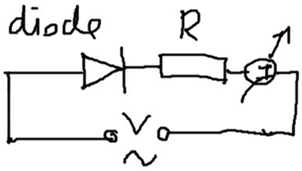




rectifier

1. single p-n junction

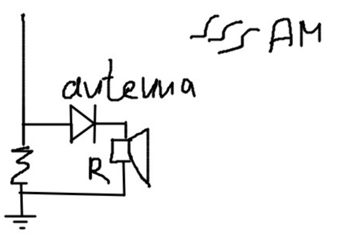
This device is the diode.

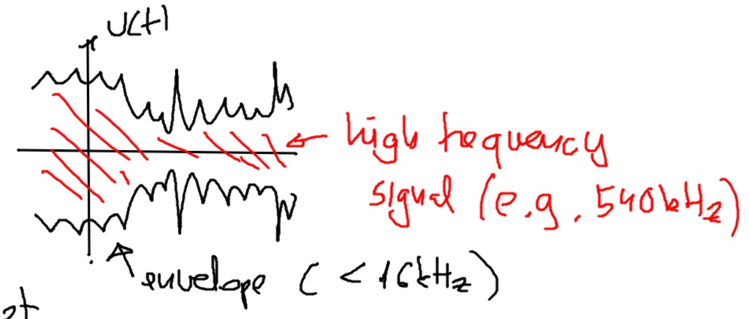


$$V = V_0 \sin\omega t \Rightarrow I(t) = \begin{cases} \frac{V_0}{R}\cdot \sin\omega t & \text{, when } V > 0 \\ 0 & V < 0 \end{cases}$$

Can be used for decoding AM (amplitude modulated) radio waves:

near the transmitter

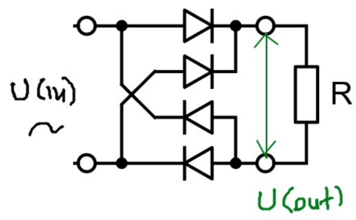


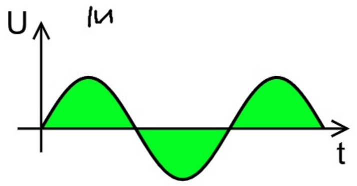


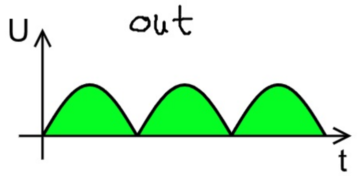
the loudspeaker cannot follow the high frequency part, only the envelope

diode: cuts out the negative part

Full wave rectifier (Graetz-bridge)





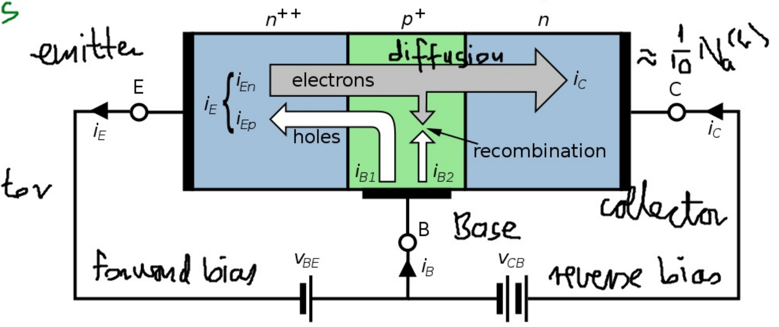


2. Bipolar Junction transistor (BJT) 1948

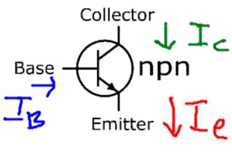
$N_d \gg N_a \approx 10 N_d$ widths $w_e \gg w_b$, $w_c > w_e + w_b$

both electrons and holes

npn transistor



in circuits



narrow base layer => small recombination, most electrons (~95%) passes through to the collector

Two different mode of operation:

a) $\Delta U_{BE} \rightarrow \Delta i_{BE} \rightarrow i_{EC} \gg i_{BE} \rightarrow \Delta U_{CE} \gg \Delta U_{BE}$ => amplifier

b) switch

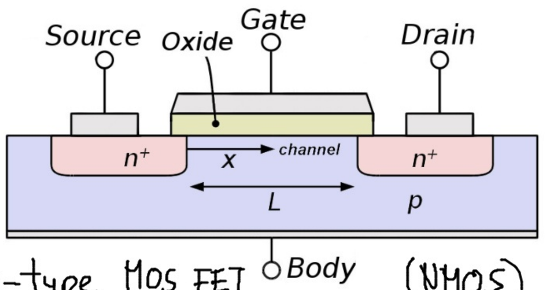
If V_{BE} too is reverse biased => no current
V_{CB} too is forward bias => max current
=> used as switch

field effect transistor - FET ← unipolar: either electrons or holes

was created in 1945, was abandoned in 1950 (for BJT) used again from 1959 as MOSFET

advantages: smaller size (higher density)
lower power consumption

⇒ used in integrated circuits
cell phones...



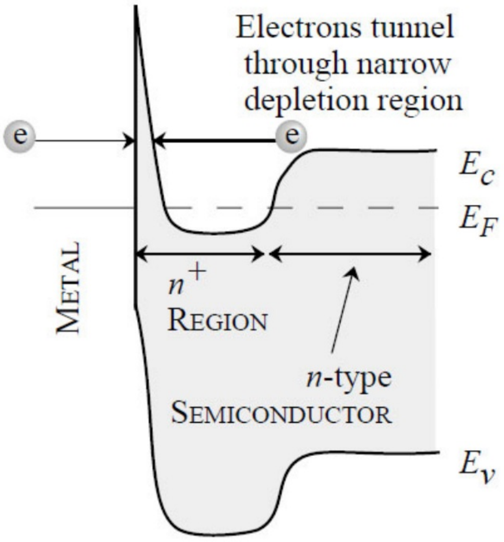
n-type MOS FET (NMOS)

U_{GS} controls a current through
- the p-type region is a channel between Source and Drain

CMOS
└ complementary MOS
⇓
logic gate from NMOS + PMOS

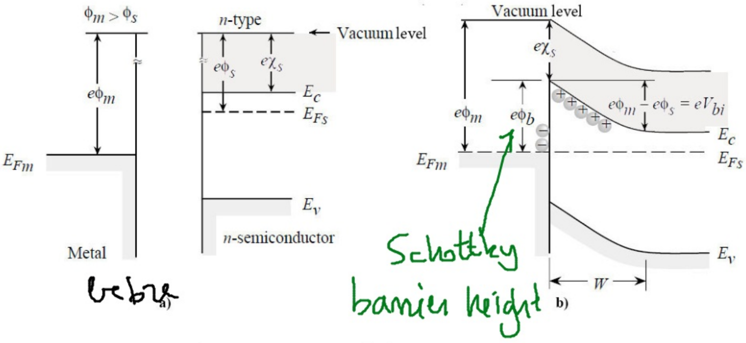
Metal-semiconductor-junctions

ohmic junctions



Schottky junction
(rectifying)

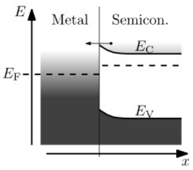
unbiased

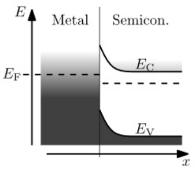


before

Schottky barrier height

(for calculating the thermionic emission formula must be used)





forward

reverse

bias

e can move into the metal

e can't move into the metal