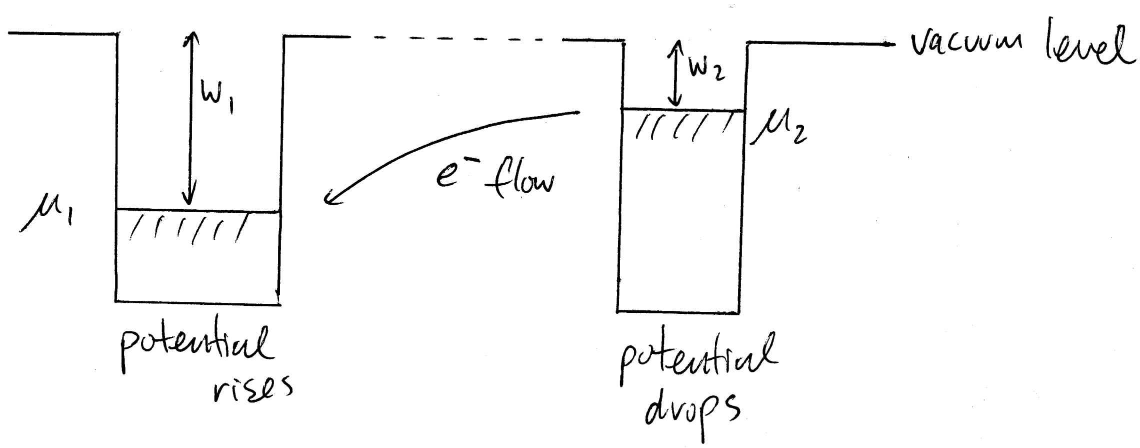
* Two conductors brought into contact

→ electrons flow from material of higher μ to lower μ

→ each material experiences a change in net charge and hence a change in electrostatic potential relative to the vacuum level



→ number of electrons transferred is tiny ; no observable effect on band filling

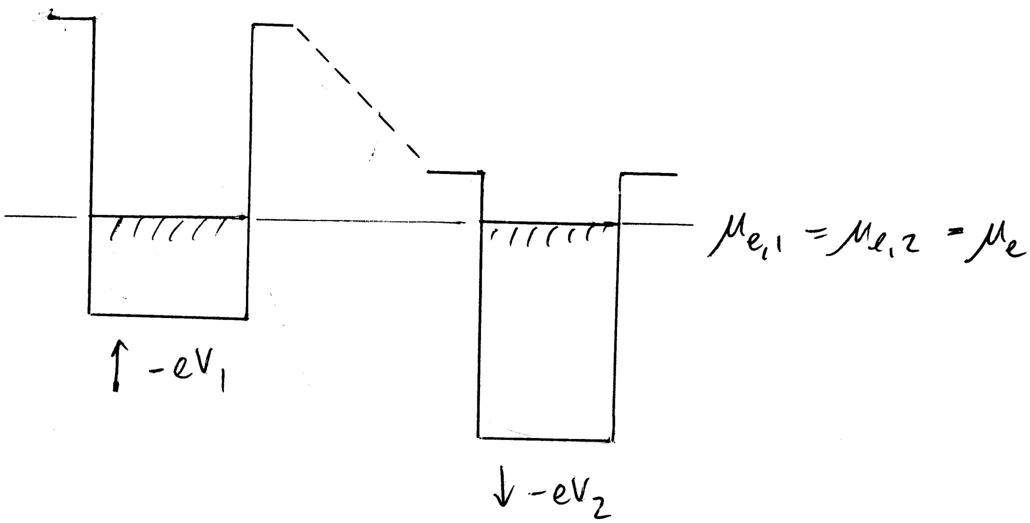
→ equilibrium reached when the electrochemical potential $\mu_e = \mu - eV$ comes into alignment

i.e. $$\mu_1 - eV_1 = \mu_2 - eV_2$$

or contact potential $V_2 - V_1 = (\mu_2 - \mu_1)/e$

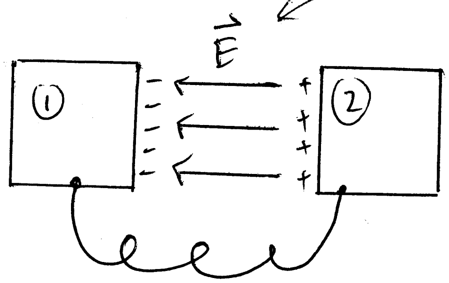
→ related to work functions by

$$V_{21} = V_2 - V_1 = (W_1 - W_2)/e$$



→ probability of occupancy for any level ε is $\dfrac{1}{1+e^{\beta(\varepsilon-\mu_e)}}$

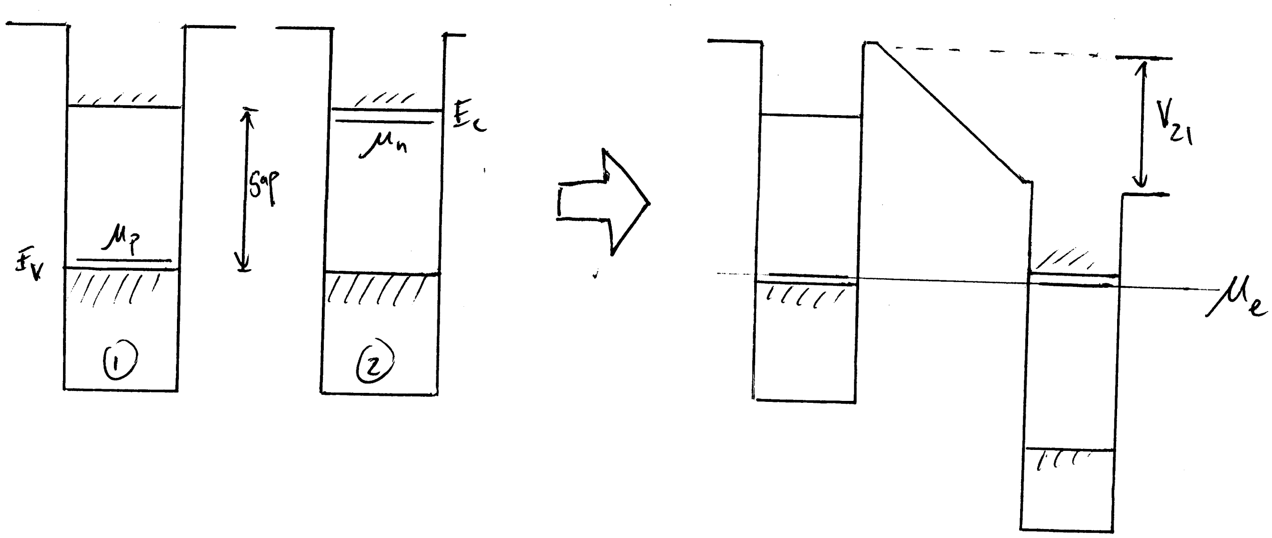
→ transferred charge generally resides on surfaces to minimize the energy

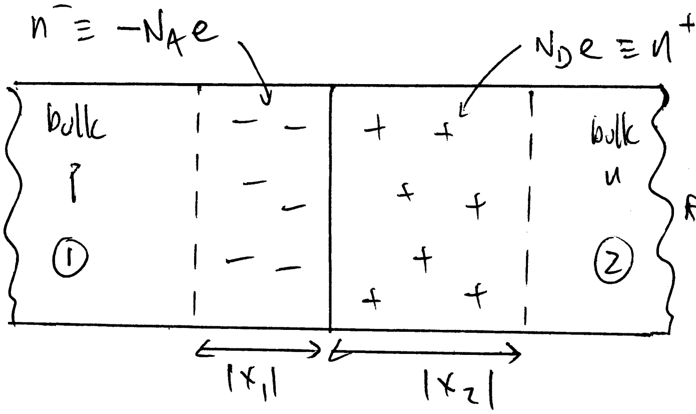


field arises due to the potential difference

$$V_{21} = V_2 - V_1 = -\int_1^2 \vec{E}\cdot d\vec{r}$$

* p-type and n-type semiconductor brought into contact



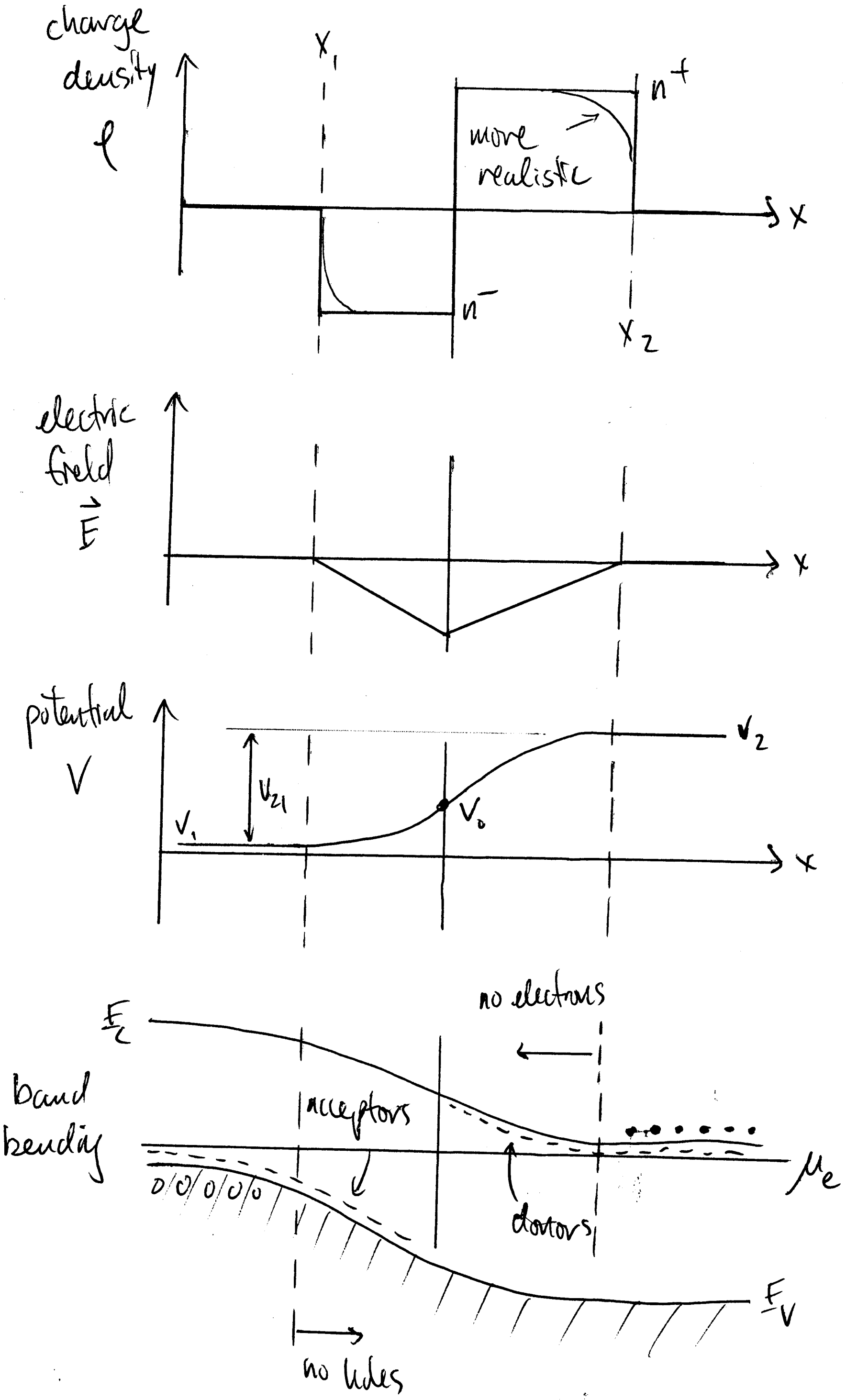


→ charge equality : $n^- x_1 = n^+ x_2$

or $N_A |x_1| = N_D |x_2|$

cross-sectional area A in y, z coordinates

→ linear electric field pointing from n-type to p-type region



$$EA = \frac{Q}{\epsilon} = -N_A e A (x - x_1)$$

$$V_0 - V_1 = \int_1^0 dV = \int_{x_1}^0 E\,dx$$

$$= \frac{N_A e}{\epsilon} \int_{x_1}^0 (x - x_1)\,dx$$

$$= \frac{1}{2} \frac{N_A e x_1^2}{\epsilon}$$

$$EA = \frac{Q}{\epsilon} = N_D e A (x - x_2)$$

$$V_2 - V_0 = \frac{1}{2} \frac{N_D e x_2^2}{\epsilon}$$

$$V_2 - V_1 = \frac{e}{2\epsilon}\left[N_A x_1^2 + N_D x_2^2\right]$$

* Contact potential $V_{21} = \frac{W_1 - W_2}{e} = \frac{W_p - W_n}{e} \approx 1$ volt,

so actual values of x_1, x_2 are highly constrained

→ e.g. $N_A \sim N_D \sim 10^{18}\ cm^{-3}$

dielectric $\epsilon \sim 10$

contact potential $V_{21} \sim 1$ volt

then $|x_1| \sim |x_2| \sim 1000$ Å

→ on the other hand, for two metals

$n^+ \sim n^- \sim 10^{22}\ cm^{-3}$

$\epsilon \sim 1$

then $|x_1| \sim |x_2| \lesssim 1$ Å no meaningful depletion region

↑ less than a lattice spacing

* Classical diffusion (Einstein)

→ particle current $\vec{j} = -D\vec{\nabla}n$ flows "downhill" along the density gradient

→ for Boltzmann occupation, $n \sim \sum_k e^{-(\varepsilon_k - \mu)/k_BT}$

and $$\vec{\nabla}n = \vec{\nabla}\mu \cdot \frac{n}{k_BT}$$

→ Corresponding charge current is

$$\vec{J} = (-e)(-\frac{D}{k_BT})n\,\vec{\nabla}\mu = \frac{eDn}{k_BT}\vec{\nabla}\mu \equiv \frac{\overset{\text{conductivity}}{\sigma}}{e}\vec{\nabla}\mu$$

→ Einstein relation

"mobility": $\sigma = ne\mu_0$

$$D = \frac{\sigma \cdot k_BT}{ne^2} \equiv \frac{\mu_0 k_BT}{e}$$

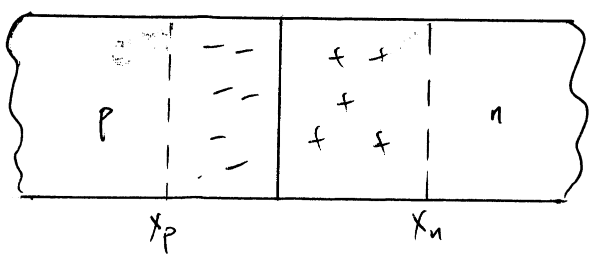
* Ohm's law in the material context

$$\vec{J} = \frac{\sigma}{e}\nabla\mu_e$$ ← follows the electrochemical potential

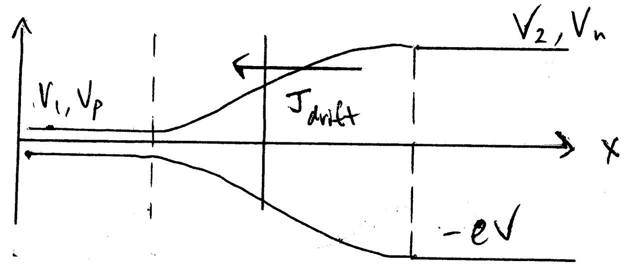
$$= \frac{\sigma}{e}\nabla\mu - \sigma\nabla V$$

$$= \underbrace{\frac{\sigma}{e}\nabla\mu}_{\text{diffusion current}} + \underbrace{\sigma\vec{E}}_{\text{drift current}}$$

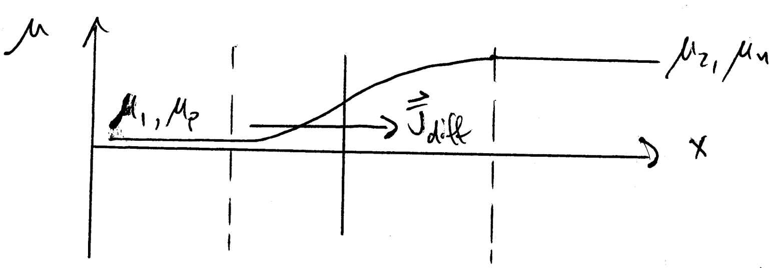
* Drift and diffusion currents in the p-n junction



→ $\mu_e = \mu - eV$ constant across the sample



$$\vec{J}_{drift} = -\sigma \vec{\nabla} V$$

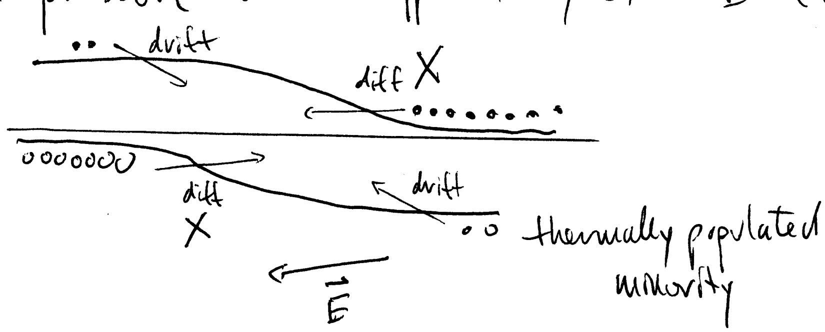


$$\vec{J}_{diff} = \frac{\sigma}{e} \vec{\nabla} \mu$$

→ no <u>net</u> current since $\vec{J}_{drift}$ and $\vec{J}_{diff}$ are equal and opposite

→ minority carriers swept along by electric field

→ majority carriers penetrate adjacent region by population pressure but are opposed by the $\vec{E}$ field



* Rectification by a p-n junction

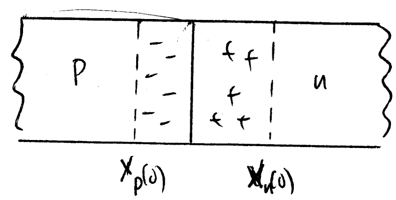
→ recall

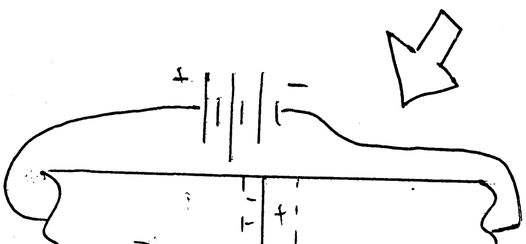
$$x_{n,p} = \pm \left[\frac{\epsilon (N_A/N_D)^{\pm 1} V_{12}}{e^2 (N_A + N_D)} \right]^{1/2}$$

→ leave the analysis the same except for the addition of an external potential V_{ext}

i.e. put $V_{12} \to V_{12} - V_{ext}$

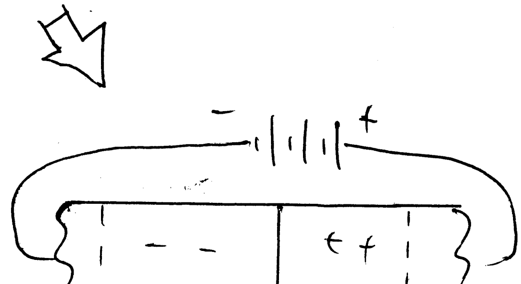
$$x_{n,p}(V_{ext}) = x_{n,p}(0) \left(1 - \frac{V_{ext}}{V_{12}}\right)^{1/2}$$





forward bias

$V_{ext} > 0$



reverse bias

$V_{ext} < 0$

→ composition of the total current

$J_{\text{hole, recombination}} = C_h \cdot e^{\beta V_{ext}}$

→

majority holes must be thermally excited over the barrier $V_{z_1} - V_{ext}$

$J_{\text{hole, generation}} = C_h \cdot 1$

←

minority holes wander into the depletion region and are swept along by the $\vec{E}$ field

$J_{\text{electron, generation}} = C_e \cdot 1$

→

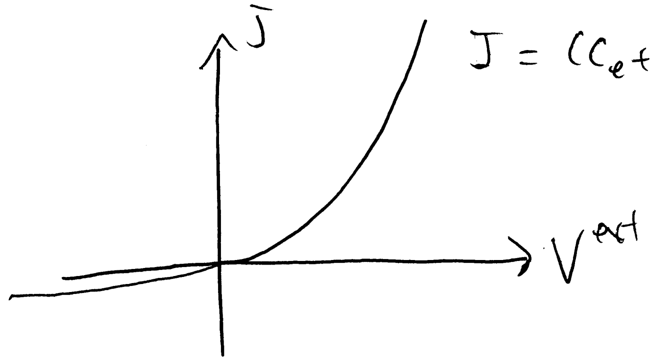
minority electrons

$J_{\text{electron, recombination}} = C_e \cdot e^{\beta V_{ext}}$

←

majority electrons

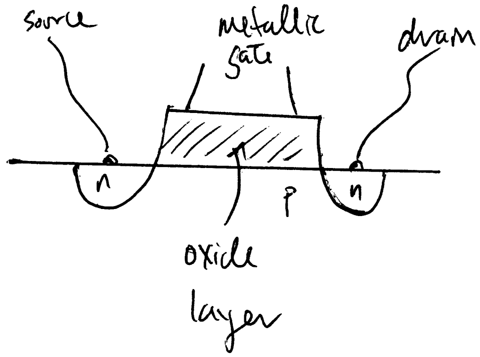
* Net current is asymmetric in the applied voltage



$J = (C_e + C_h)(e^{\beta V_{ext}} - 1)$

diode

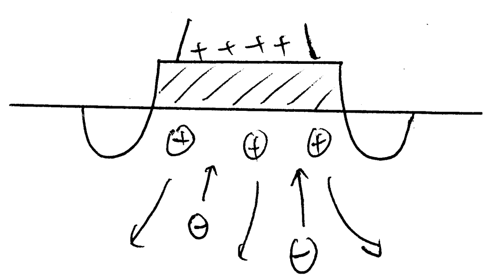
* Metal Oxide Semiconductor Field Effect Transistor (MOSFET)



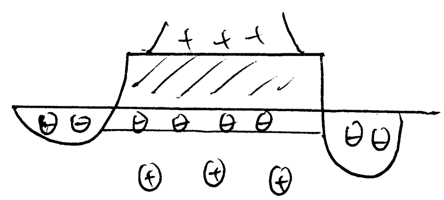
→ variable mode of operation depending on whether a votage is applied to the gate

① in the absence of a gate voltage, there is a large barrier to current flow from source to drain

② if the gate votage is turned up, positive charge will pile up against the oxide:



as a result nearby holes in the p-type region are repelled and electrons attracted



an "inversion layer" with majority electron carriers is established that connects source to drain

→ hence, the gate acts as a switch that turns on or off the current flow through the device

→ band bending picture