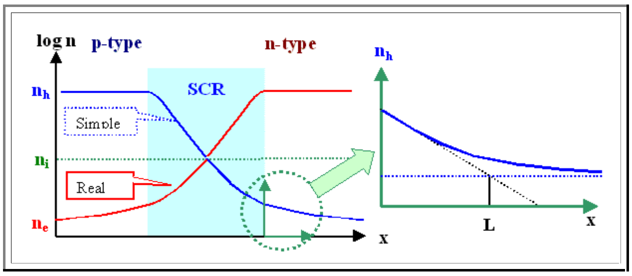
Junction Diodes With Small Dimensions

Advanced

Lets first look at the basic situation as we had it before for *large* diodes:



We have an excess of minority carriers at the edge of the space charge region stemming form the majority carriers injected into the other part of the junction.

- The difference of the actual concentration $n^{p,n}{}_{e,h}(U)$ and the equilibrium concentration $n^{p,n}{}_{e,h}(U = 0)$ was given by

$$\Delta\, n^{p,\,n}{}_{e,\,h}\Big|_{\substack{\text{edge}\\ \text{SCR}}} \;=\; n^{\,p,\,n}{}_{e,\,h}(U) - n^{\,p,\,n}{}_{e,\,h}(U = 0) \;=\; n^{p,n}{}_{e,h}(\text{equ}) \cdot \left(\exp\frac{U}{kT} - 1\right)$$

Neglecting the **– 1** for forward conditions, we have the exceedingly simple *general relation* that the current flowing is simply the diffusion current at the edge of the **SCR** following from the concentration gradient via Ficks **1st** law. Lets look at this a bit closer.

- All that counts is the slope $d\Delta n^{min}/d\,x$ of excess minority carrier concentration at the edge of the **SCR**. It gives directly the minority carrier current at the edge of the **SCR** - and that is the only current we need to consider.
- Since it is the *only* component of the current flowing at this point of the junction, (we neglected the other principal terms for the forward condition), and since the current is constant throughout the junction, it simply is *the* current. We don't have to worry about the other side of the junction or anything else.
- The junction current j thus is

$$j \;=\; -\,q \cdot D \cdot \frac{d\Delta n^{min}}{dx}\Big|_{\substack{\text{edge}\\ \text{SCR}}}$$

What about the current deeper in the **Si**? The slope is smaller and this must lead to a smaller current, too. Yes - but now we have a *majority carrier current*, too. Whatever we loose due to recombination in the minority carrier current component, we gain in the majority carrier current component and the total current stays constant.

In order to compute it, we need the slope and thus $\Delta n^{min}(x)$.

- We *always* obtain $\Delta\, n^{min}(x)$ as the solution of a diffusion problem, taking into account boundary conditions, e.g. $\Delta\, n^{min}(x = 0)$, i.e. at the edge of the **SCR**, or the disappearance via recombination.
- One boundary condition is clear: At the edge of the **SCR** the excess concentration will be at a fixed value controlled by the applied potential as described above .
- The second boundary condition is less clear. When we derived the relation

$$\Delta n(x) \;=\; \Delta\, n_0 \cdot \exp -\frac{x}{L}$$

- we also got the current

$$j^{\,min}(x = 0) \;=\; \frac{q \cdot D}{L} \cdot \Delta n^{min}(x = 0)$$

- we implicitly assumed that the size of the diode was infinite and that minority carriers simply disappear by recombination.

For a *small diode* now, with ***x***-dimensions much smaller than ***L***, we have to reconsider the diffusion problem.

- Assuming that after a distance $d_{Con} \ll L$ we now have an ohmic contact, we must ask what the excess minority carrier density will be at $x = d_{Con}$.
- To make life easy, we now simply include in the *definition* of a "good" ohmic contact that minority carriers reaching it will recombine instantaneously. While this is pretty much true for real contacts, it is not necessarily obvious.
- With this assumption we simply have as the important boundary condition for a small diode .

$$\boxed{\Delta n(x = d_{Con}) \;=\; 0}$$

This makes the solution to the diffusion problem very simple.

- Since practically no recombination in the bulk will take place - all minorities die at the contact - the current *everywhere* is simply the minority carrier current. This necessitates that

$$\frac{\mathrm{d}\Delta n^{min}}{\mathrm{d}x} = \text{const} = -\frac{\Delta n^{min}\big|_{\text{edge SCR}}}{d_{Con}}$$

- The current then is

$$j^{\,min} = j = -\,q\cdot D\cdot \frac{\mathrm{d}\Delta n^{min}}{\mathrm{d}x}\bigg|_{\substack{\text{edge}\\ \text{SCR}}} = \frac{q\cdot D}{d_{Con}}\cdot \Delta n^{min}\,(x = 0)$$

This is exactly the same formula as for the large diode - *except* that we now have d_{Con} instead of L as the important length scale of the device.

- Moreover, minority carriers will now disappear by recombination at the contact after an average time τ_{trans} called **transit time** given by the time they need for traveling the distance d_{Con}. Obviously, we have

$$\boxed{d_{Con} \;=\; \left(D\cdot\tau_{trans}\right)^{1/2}}$$

- in complete analogy to the relation between lifetime and diffusion length

Of course, this is still a rather simple description of a small diode. We only restricted *one* dimension, since we still treated a one-dimensional case.

- Real diodes might be small in more than one dimension, and all kinds of other complications can be imagined. Nevertheless, the device dimensions and the transit time will in one form or other replace the bulk diffusion length and lifetime.
- The importance of this can not be overestimated. Device sizes in integrated circuits are in the **sub-µm** region and critically influence device behavior.