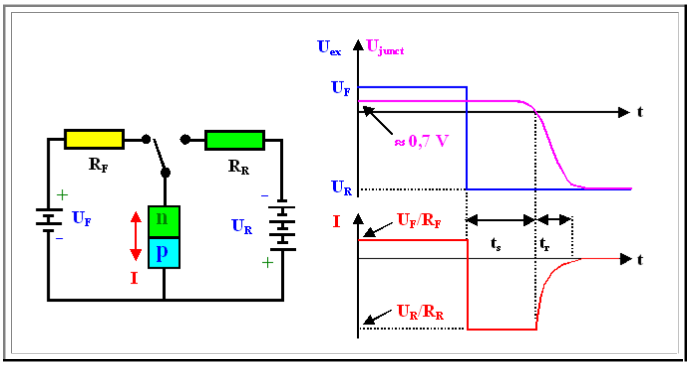
Reverse Recovery Time of Junction Diodes

Advanced

- The basic situation is shown in the figure in the backbone module which will be repeated here in a somewhat more detailed fashion.



- We switch from a forward condition to a reverse condition at some time. The external voltage (blue lines in the diagram) is supposed to change suddenly (we have an ideal switch)
  - What we would measure in terms of the junction voltage and the junction current is shown in magenta or red, respectively.
  - The outstanding feature is the "reverse recovery", the reverse current flowing for some time after we switched the voltage. Right after the switching it will be limited to U_R/R for a time t_s, because we can not drive more current than that through the circuit. But after t_s seconds, the current decays with some time constant t_r until it reaches the small (zero in the picture) static reverse current of the junction.
  - If we look at t_r quantitatively, we take it to be the time it takes the current to decay to **10%** of the plateau value.
  - Can we calculate this behavior, which of course is the crucial behavior for the large signal switching of a **pn-**junction?
- Well **-** not without some problems. But we can understand what others have calculated. Let's see.
  - During static forward behavior, we have a surplus of minority carriers a the edge of the space charge region, and this surplus concentration has to disappear after we switch to reverse conditions. We looked at that in some details before, and we already have some equations for this case
  - We have to solve the relevant diffusion equation as given in the link above, but now for different conditions. Before, we looked at the static case (i.e. $\partial n^{min}(x,t) / \partial t = 0$, now we want to calculate how the minority carrier concentration changes in time.
  - So, once more, we have to solve the relevant continuity equation. We do it for one side of the junction only; the other side then is trivial.

$$\frac{\partial\, n^{min}(x,t)}{\partial t} = D \cdot \frac{\partial^2 n^{min}(x,t)}{\partial x^2} - \frac{n^{min}(x,t) - n_0}{\tau_{eff}}$$

  - The last term simply governs the disappearance of carriers by recombination; otherwise we just have Ficks second law. For τ_{eff} we have to take the minority carrier lifetime τ or the transit time τ_{trans} as the geometry demands (in-between situations are messy!).
- If we have the solution for $n^{min}(x, t)$, we can calculate everything else easily, the voltage across the junction. e.g. is always

$$U_{junct} = \frac{kT}{q} \cdot \ln \frac{\Delta\, n^{min}(x, t)}{n_0}$$

- Now we have to look at the boundary conditions for the problem
  - If you look at the picture above long enough, you realize that as long as U_{junct} is positive, the boundary conditions are

$$I_R = \frac{U_R}{R_R} = q \cdot D \cdot \frac{\partial n^{min}(x,t)}{\partial x}$$

- As soon as $U_{junct} = 0$ **V**, the boundary conditions need to be changed to

$$n^{min}(0,t) = n_0$$

- You don't see it? That's OK, at least for the second case. The boundary conditions are actually only approximations, and would take a lengthy discussion to justify them (in particular the second one and the switch over point) in detail. So just believe it.

Now it is math - solving differential equations with certain boundary conditions. Not so easy, but doable. According to Kingston (**1953**), the solutions for the two time constants t_s and t_r are (in implicit form)

$$\frac{1}{1 + I_R/I_F} = \text{erf}\left(\frac{t_s}{\tau_{eff}}\right)^{1/2}$$

$$\text{erf}\left(\frac{t_r}{\tau_{eff}}\right)^{1/2} + \frac{\exp -(t_r/\tau_{eff})}{\pi \cdot t_r/\tau_{eff}} = 1 + \frac{0{,}1 \cdot I_R}{I_F}$$

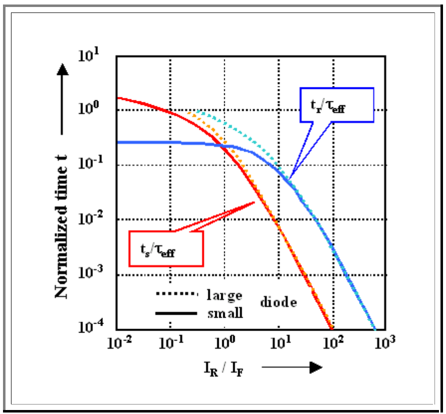
- with **erf** = error function as we know it from diffusion problems.

OK. May the force be with you when you try to prove these solutions or just to extract data. Only one thing is clear: We better look at the ratios t_s/τ_{eff} and t_r/τ_{eff} than at the t's directly.

- Well, there are always the approximations, which we are going to use here:

$$t_s + t_r \approx \frac{\tau_{eff}}{2} \cdot \frac{I_F}{I_R}$$

Even better, there are complete solutions in graphical form:



- The solid lines are for the "small" diode, where we have to take the transit time for τ_{eff}, the dashed line indicate the "large" diode case.

It is clear that you really can achieve much larger switching speeds for a given τ_{eff} by being smart about I_R/I_F, i.e. if you increase I_R (or decrease I_F, but that is rarely an option)

- However, don`t forget the prize you have to pay: Large reverse currents while "idling" = large losses = heating your device.

This is the first inkling we get that there is some *trade off between speed and power*.