

## 3.4 Basic Silicon Devices

In this subchapter 3.4 we look at typical **Si** devices from two angles:

**First**, the very basics of more or less *ideal* devices are given in rather short notation. This should be a reminder and not something new for you.

**Second**, some relevant facts about *real* devices are presented without much deduction.

Some of this will be needed and come up again in chapter 8 "[Speed](#)".

### 3.4.1 Junction Diodes

#### The Ideal Junction Diode

The ideal - in the sense of most simple - **Si** junction diode has essentially one major property:

Its ***I-U characteristic*** can be described to a very good approximations by the "[simple](#)" **pn-junction theory** containing the contribution of the space charge layer (otherwise you are not really describing a Si device at all). We had

$$j = \left( \frac{e \cdot L \cdot n_i^2}{\tau \cdot N_A} + \frac{e \cdot L \cdot n_i^2}{\tau \cdot N_D} \right) \cdot \left( \exp - \frac{eU}{kT} - 1 \right) + \frac{e \cdot n_i \cdot d(U)}{\tau} \left( \exp - \frac{eU}{2kT} - 1 \right)$$

The major variables are the **doping levels** **N** (determining the **SCR** width **d**, too), the **diffusion length** **L**, (same thing as the [life time](#)  $\tau$ , since they are coupled by the **Si** diffusion constant **D**, which again is [directly connected to the mobility](#)  $\mu$  of the carriers, which finally is mainly a [function of doping](#)), the temperature **T**, and, of course, the junction voltage **U**.

When does this equation break down, i.e. what distinguishes an "*ideal*" junction diode from a "*real*" one?

**First**, with just that equation, you could increase the **voltage** to any value you like, and the equation gives some **current** which might become very large for forward bias, and would stay small for arbitrarily large reverse bias. That is **not** realistic, of course.

At large reverse voltages, we have a large electric field in the **SCR**, and at some point we will just have **electrical breakdown** since no material can withstand arbitrarily large field strengths. The breakdown mechanism is usually **avalanche breakdown**.

Very large forward currents are also not realistic. The [real I-U characteristics](#) shown before indicates some reasons. One thing that goes wrong is that our equation does not treat the case of **high injection**, meaning that the concentration of minority carriers injected into the junction is larger (or at least comparable) to the equilibrium concentration in the bulk. Somewhere in the derivation of the basic diode equation we always made an assumption (hidden or openly) of **low injection**, so we cannot expect real diodes to behave ideally for **large** forward currents.

**Second**, we have totally neglected the **ohmic resistance** of the **Si**.

Whatever its value **R<sub>ser</sub>** might be, it can be seen as being switched in series to the actual diode and thus will reduce the junction voltage **U<sub>junct</sub>** to

$$U_{\text{junct}} = U_{\text{ex}} - I \cdot R_{\text{ser}}$$

In other words, we now must distinguish between the external or terminal voltage **U<sub>ex</sub>** and the junction voltage **U<sub>junct</sub>**, and there simply is no way to pass currents larger than **U<sub>ex</sub>/R<sub>ser</sub>**.

**Third**, we certainly must have some reservations about the **doping** in the derivation of the equations, too.

The **concentration** **N** certainly cannot have any value. But limits here are not very important, because for the level of doping achievable in real Si diode, the equation is not too bad.

More important are **gradients** in the dopant concentration, i.e. **dN<sub>Acc</sub>/d x** because we assumed (implicitly) that **N** is constant; which it rarely is in real diodes.

**Fourth**, we have to be a bit concerned about the **temperature**.

The validity of the equation with respect to **T**-variations is limited: Somewhere we assumed that all dopants are ionized and that the Fermi energy is close to the band edges which will certainly not be true at any temperature..

In practical terms this means that we are restricted to temperatures not too far off room temperature.

**Fifth and last**, we have to consider the **diffusion length** **L**.

- While we might worry a bit about the allowable range - is the equation still correct for very large or very small  $L$  - the real problem is different:
- Make an ideal diode from **Si** with  $L = 200 \mu\text{m}$ , for example (a regular value), and then make the **diode small** - lets say you just leave  $1 \mu\text{m}$  of **Si** to the left and right of the **SCR**. Since  $L$  was the average distance an electron or hole traveled in the **Si** before death by recombination, we have a problem now. The bulk value of  $L$  obviously can no longer summarily describe the perambulation of a minority carrier.
- Looking at it more quantitatively, we must modify the distribution of minority carriers from the edge of the **SCR** into the bulk of the **Si** for forward current flow as it was dealt with in subchapter [2.3.4 "Useful Relations"](#) and in subchapter [2.3.5 "Junction Reconsidered"](#). Lets look at this in an [advanced module](#), here we only look at the results.

## The Real Junction Diode.

Lets see summarily what we must change to account for the items 1 - 5 above.

*First* we look at intrinsic *voltage and current limitations*.

- Avalanche *breakdown* will occur whenever the field strength in the **SCR** manages to impart enough energy to an electron or hole to generate more carriers in some scattering process. While it is clear that the field strength in the **SCR** is mainly a function of doping, it is not so easy to derive numbers.
- There are more breakdown mechanisms than just carrier multiplication by avalanche effects; most important, perhaps is tunneling of carriers through the potential barrier at the junction. Again, high field strengths help.
- Important are the practical limitations in terms of usable reverse *voltages* (not field strengths per se). The range of admissible reverse voltages is large and reaches from  $> 1000 \text{ V}$  for lightly doped **Si**, say  $10^{14} \text{ cm}^{-3}$  (and some sophisticated technology) to just a few Volts on the highly doped end - take  $10^{18} \text{ cm}^{-3}$ .
- Forward currents in the *high injection mode* of a real diode will be smaller than predicted by the ideal equation. In a first approximation, we simply have to reduce the slope of the characteristic by a factor of 2 - we have the same slope as in the **SCR** dominated part at very small forward currents.
- This is what is shown in the curve for a real diode in the [picture we used before](#).

*Second*, how about the *ohmic resistance*?

- It is certainly not negligible in many real diodes and is one of the major problems in [solar cells](#).
- It is, however, easy to address. Just do it yourself in a little exercise.

### Exercise 3.4.1

Current-Voltage characteristics of a  
solar cell with series and shunt  
resistance

*Third*, we consider *doping gradients*.

- This is certainly the realistic case, because real diodes are mostly made by diffusing **n** or **p**-dopant into a **p** or **n**-doped substrate, respectively. At least one side of the diode thus has a doping that varies strongly with the distance from the actual junction (located at the point where  $n^e = n^p$  or  $N_{\text{Don}} = N_{\text{DAcc}}$  . [Typical profiles](#) are given in the link
- How do doping gradients influence the current-voltage characteristics?

The surprising answer is: *Not much at all!* (Take that with a grain of salt)

- The reason is that no matter how you derive the  $I(U)$  characteristics, the decisive parts are only the height of energy barriers, and the recombination/generation/diffusion behavior outside the space charge region. The precise shape of the band bending, or the width of the **SCR** does not enter at all, or at best weakly (in the **SCR** term via  $d_{\text{SCR}}$ ) in the basic equation [from above](#).

What will be influenced by doping gradients are: *First*, (minor) parameters like resistivity and mobility, and *second*, the **SCR** properties like its size, and especially its **capacitance**.

- The first group changes the pre-exponential factor  $L \cdot n_i^2 / \tau \cdot N_{\text{dop}}$  somewhat; essentially you replace the formerly constant  $N_{\text{dop}}$  by some kind of average resulting in an effective doping  $N_{\text{eff}}$ .
- These second set of parameters resulted from solving the Poisson equation, and we have only [done this for constant dopant concentration](#). Redoing the calculations for *real* dopant profiles must generally be done numerically.

However, the minor effects of doping gradients on the **DC** (direct current) current-voltage behavior must not induce you to think that doping gradients are unimportant!

- The **AC** behavior, or, in other words, the *speed* of the junction, is very much influenced by **SCR** properties and thus by dopant gradients.

- More to that in [chapter 8 "Speed"](#).

Fourth, a quick glance at temperature effects

- Typical  $T$ -specifications for **Si** devices are  $0\text{ }^{\circ}\text{C} < T < 70\text{ }^{\circ}\text{C}$  for typical consumer integrated circuits or  $-55\text{ }^{\circ}\text{C} < T < +125\text{ }^{\circ}\text{C}$  for somewhat better stuff.
- Pushing technology and materials gives maybe  $+160\text{ }^{\circ}\text{C}$  for an admissible operation temperature of **Si** devices.

While it is not only the **pn**-junction that limits the temperature region for applications of more complex devices, you simply must make sure that you have sufficient carriers (i.e.  $T$  cannot be too low), but not too many (i.e. carrier concentration must be controlled by doping and not by thermal band-band generation), limiting the upper temperature.

Fifth and last, how does the size of the device influence its properties?

- There is simple answer for simple (one-dimensional) small diodes: Replace the diffusion length  $L$  by a relevant length of the device, e.g. the distance between the edge of the **SCR** to the ohmic contact  $d_{\text{Con}}$  in all equations, and concomitantly the life time  $\tau$  by the transit time  $t_{\text{tran}}$  defined via

$$d_{\text{Con}} = \left( D \cdot t_{\text{tran}} \right)^{1/2}$$

- The justification is given in an [advanced module](#).
  - In other words, we equate some relevant length  $d_{\text{Con}}$  of the device with the average distance that minority carriers travel before they disappear, and  $t_{\text{tran}}$  is the time they move around.
- This makes not only immediate sense but has far-reaching consequences, as we will see, e.g. in [chapter 8](#). Some major points are listed below:
- The size (together with the mobility) becomes the most important parameter for *speed*.
  - Since vertical dimensions are more easily made small than lateral ones, bipolar devices in a vertical stack are inherently faster than lateral **MOS** devices. In-diffusion of dopants, e.g., defining the depth of a **pn**-junction, is easily restricted to **0,1  $\mu\text{m}$** ; while it takes very advanced technology to produce lateral structure sizes in this region.
  - Leakage currents decrease with decreasing device size.

One (of several) incentives to make devices ever smaller has its roots right here.

Well, the long and short of this is that *real* diodes are quite different from *ideal* ones - in the details! The global topics stay unchanged, let's recount them quickly:

- - Majority and minority carrier dynamic equilibrium in the bulk, controlled by doping, carrier life time and mobility
  - Energy barrier at the junction, resulting in **SCR** and carrier concentration gradients
  - Very different behavior in reverse and forward direction
  - Forward currents mostly resulting from diffusion currents removing injected minorities
  - Reverse currents mostly resulting from field currents affecting minorities at the edge of the **SCR**

In practice, "ideal large" diodes practically do not exist (except in the form of solar cells). Even "small" diodes with graded junctions and the like are not really used if you need a diode (but as part of more complicated devices like **MOS** transistors). Technical diodes are more sophisticated since they are optimized for specific parameters, e.g. extremely large breakdown voltages. A few examples are

- The **PIN diode**, short for: **p**-doped - **i**ntrinsic - **n**-doped. A thin layer, as intrinsic as possible, is sandwiched between doped **Si**. Good for large forward currents and large reverse voltages. This is the standard form for diodes use for rectifying purposes.
- **Tunnel diodes**, **varactors**, fast recovery diodes, **Gunn** diodes, **IMPATT** diodes, **Zener** diodes, **solar cells** - there is no shortage of names for special diodes and applications going with it. We will, however, not dwell on the subject here (in time, maybe, there might be advanced modules).