2.2.4 Simple Junctions and Devices

In this section we will look at some **junctions** in a cursory manner with the goal to get a basic understanding for current flow and the driving forces behind it.

- We will see that it is possible (with only a little cutting of corners) to come to a complete quantitative description of the current–voltage relationship of a **p–n** junction; even including the (usually omitted) *generation current* part, without doing a lot of math.
- We will do this in three steps: First we look at a *hypothetical* junction, then at the *classical **p–n** junction*, then at a *real* **p–n** junction with recombination and generation currents in the space charge region.

But don't deceive yourself! These are *difficult* subjects, even if they are made to look relatively easy here.

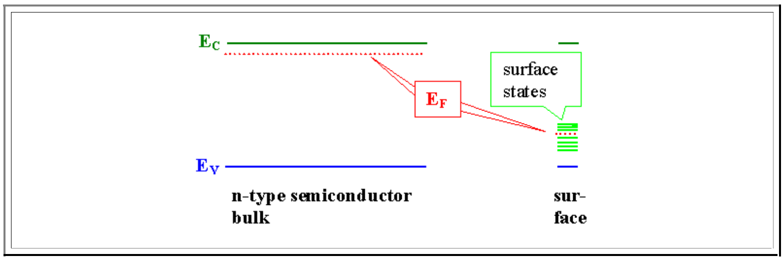
- We will delve somewhat deeper into these subjects later. However, within the scope of this course, there will not be enough time to go into junction theory thoroughly and in depth.
- Here we only attempt to give enough background knowledge, so you can understand the rigid treatment of device physics that can be found in many books.

Equilibrium Between a Semiconductor and its Surface as a Model

First, we must realize that the surface is a *defect* – beyond it, there is no periodic lattice anymore; the bonds of the surface atoms have some other arrangements than the bonds in the bulk.

- The dispersion relation of electrons in the two-dimensional surface "crystal" thus must be expected to be different from that of the bulk.
- In the simplest approximation conceivable, we may picture the surface with the same band diagram as the bulk (but in only two spacial dimensions), but with plenty of additional states in the band gap.

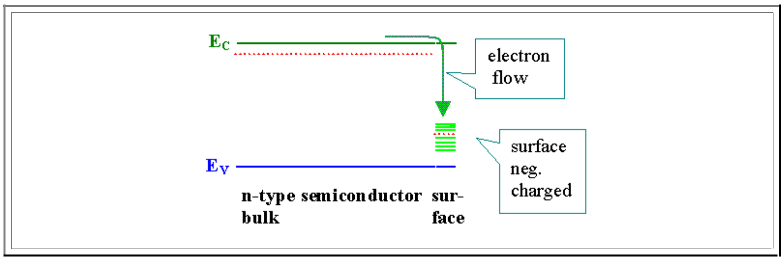
We have then the following representation:



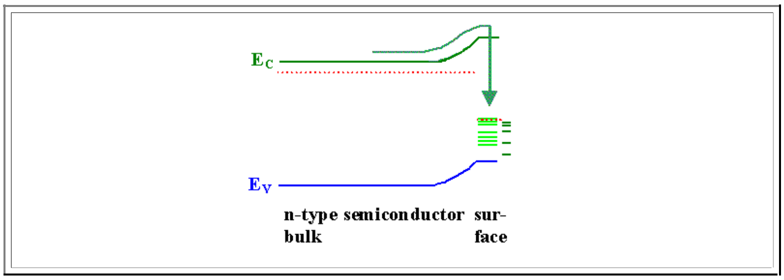
- The surface introduces some unspecified states in the band gap of an **n**-type semiconductor, shown here arbitrarily as acceptor states. The Fermi energy will adjust itself as shown: Since states in the bandgap are available that are lower than the donor states (not shown for graphic simplicity), electrons will move down to these states – so the Fermi energy also comes down.

We will now consider what would be happening if we were to bring the bulk and the surface in close contact. Shown here are three graphical representations of this (fictitious!) process:

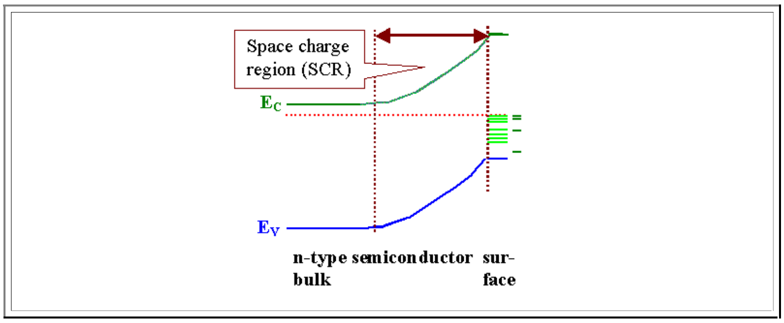
- Upon contacting, the electrons from the conduction band of the bulk will flow to the still empty states of the surface. This will put an additional negative charge at the surface. (Note that before that, the surface was not charged.)



- In response to the negative surface charge, the electrostatic potential at the surface goes up and extends (decreasingly) into the bulk – we have an **internal potential** $V(x)$. The simplest way to visualize the **band bending** going with this potential is to remember that the electrons from the bulk are repelled by the negative surface charge. Since work is needed to move them to the surface, this is an "uphill" process. (Remember that the band diagram gives the energy of the electrons.)



- As long as the total energy can be reduced by moving electrons from the bulk to the surface, the process will continue. (Remember that energy minimization is the way towards equilibrium.) Equilibrium is reached as soon as it makes no difference any more if one more electron is in the bulk or on the surface, i.e., if we change the electron amount by Δn_e. This means that equilibrium is given by $\mathbf{0 = dG = (\partial G/\partial n_e)_{bulk} \cdot \Delta n_e(bulk) + (\partial G/\partial n_e)_{surface} \cdot \Delta n_e(surface)}$.



- From the obvious relation $\mathbf{\Delta n_e(bulk) = -\Delta n_e(surface)}$ it follows that in equilibrium, we have $\mathbf{(\partial G/\partial n_e)_{bulk} = (\partial G/\partial n_e)_{surface}}$. Since $\mathbf{(\partial G/\partial n_e)}$ = chemical potential $\boldsymbol{\mu}$ = Fermi energy E_F, this means that:

$$E_F(\text{bulk}) = E_F(\text{surface})$$

This is a crucial point; let's make it again:

In thermal equilibrium, the Fermi energy E_F is the same everywhere.

- If you are not too sure about this, read up about the concept of the chemical potential in the basic module.

This automatically leads to an imbalance of charge, we now have *local violations of charge equilibrium*.

- The area with the band bending will not contain free electrons, but still the positively charged donor atoms (= "ionized"), it thus contains *charges fixed in space* and is called a **space charge region** (***SCR***).
- The **SCR** also contains an electrical field $\underline{E}$ which is given directly by the derivative of the electrostatic potential V by $\underline{E} = -\nabla V$ (or, for the one-dimensional case, by $E_x = -dV/dx$), or it can be obtained via the Poisson equation.

The Space Charge Region

The easiest way to think about this electrical field is to consider the *field lines*, which start at a positive charge and end at a negative charge.

- The negative charges are the surplus electrons sitting in the surface states (and thus also in real space at the *surface*), the positive charges are the "ionized" donor atoms in the *bulk*.
- This view immediately leads to a "quick and dirty" formula for the width d of the space charge region: We consider the **capacitance C_{SCR}** of the **SCR**.
- Since the positive charges are spread homogeneously through the volume of the **SCR**, we approximate the capacity of the **SCR** by a plate capacitor with *half* the distance d between the plates, i.e., $d_{cap} = d/2$. In other words, we sort of put all the positive charge on a fictitious plate at half the width of the **SCR**.
- The capacitance then becomes

$$C_{SCR} = \frac{2\,\epsilon_r \cdot \epsilon_0 \cdot A}{d} = \frac{Q}{U}$$

- With A = area of the capacitor plates, Q = charge on the plates and U = potential difference between the plates.
- The charge on the plates is equal to the number of ionized donors in the volume of the **SCR**. The volume is $d \cdot A$ and the number of charges is just the density of donors N_D (assuming that all are ionized) times the elementary charge **e** times the volume $d \cdot A$, so we have

$$Q = e \cdot N_D \cdot d \cdot A$$

- Substituting this in the equation from above, we obtain

$$\frac{2\,\epsilon_r \cdot \epsilon_0 \cdot A}{d} = \frac{e \cdot N_D \cdot d \cdot A}{U}$$

This gives us one of the more important semiconductor device equations in its simplest form – and this is the *correct* equation despite the somewhat questionable assumption of $d_{cap} = d/2$:

$$d = \left(\frac{2\,\epsilon_r\,\epsilon_0\,U_{bi}}{e\,N_D}\right)^{1/2}$$

The voltage U_{bi} is the difference of the values of the internal potential between the bulk and the surface; it is called the **built-in potential**. Here, of course, it is simply the difference of the Fermi energies expressed as a potential, i.e.

$$U_{bi} = \frac{\Delta E_F}{e}$$

- We immediately can generalize: If, in addition to the "built-in" potential $\Delta E_F/e$, an additional external potential U_{ex} is added from the outside by simply connecting the material to a voltage source at U_{ex}, the total voltage becomes $U = \Delta E_F/e + U_{ex}$, and the width of the space charge region is

$$d = \frac{1}{e} \cdot \left(\frac{2\,\epsilon_r \cdot \epsilon_0 \cdot (\Delta E_F + e \cdot U_{ex})}{N_D}\right)^{1/2}$$

- Note that, since the built-in potential U_{bi} is taken to be positive, a positive U_{ex} will increase the width of the space charge region – by increasing the potential difference between bulk and surface.

It is easy to to obtain the same equation by integrating the **Poisson equation** for this case. This is done in an illustration module.

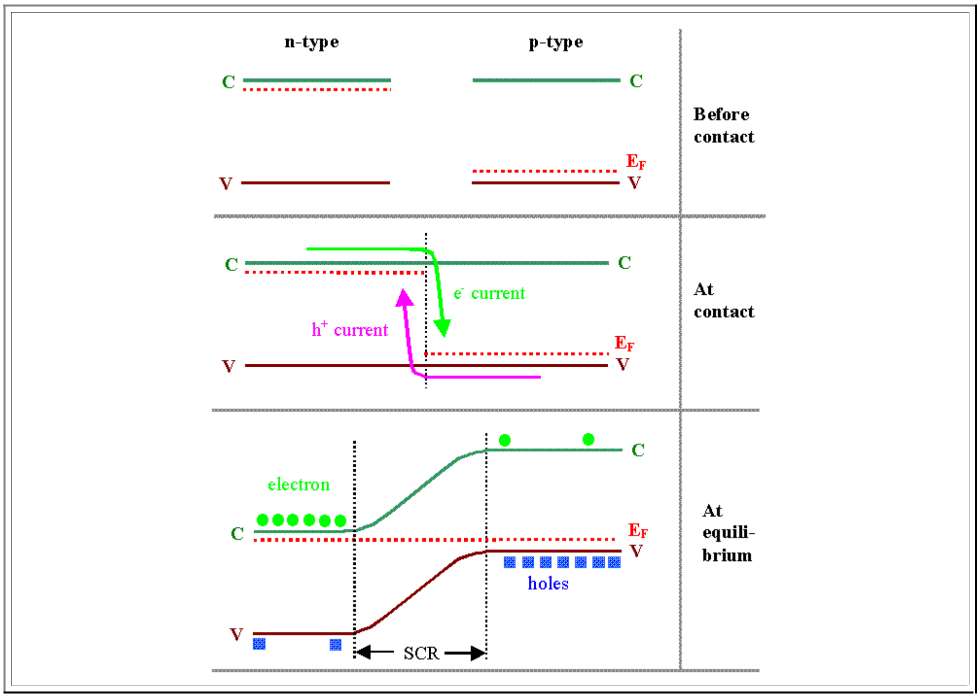
- This example illustrates nicely the approach we take in this chapter: We start from the most simple consideration of the case and try to deduce proper relations and formula by analogies – cutting corners a little if necessary (but only as long the results are still correct).

"Ideal" p–n Junction

We now construct a **p–n** junction exactly along the recipe given above:

- Draw the band diagrams of both parts.
- Join the two parts, move electrons to the materials with the lower Fermi energy, holes opposite.
- Build up space charges and shift the potentials accordingly until the *Fermi energy is the same everywhere*.

These steps are illustrated below:



- As a graphical aid, which will be useful in cases to come, the carriers are schematically indicated as circles (electrons) and squares (holes). Many such symbols being present is meant as an indication for majority carriers, whereas few ones being present indicates the minorities.

The only differences to the first situation is that we now have a space charge region on both sides of the junction.

- The field lines are now pointing from the positively charged donors on the **n**-type side to the negatively charged acceptors on the **p**-doped side.
- The width of the space charge region is now a little more involved to calculate (but there is nothing new); it comes out to

$$d = \frac{1}{e} \cdot \left(2 \cdot \epsilon_r \cdot \epsilon_0 \cdot \left(\frac{1}{N_A} + \frac{1}{N_D}\right) \cdot \left(\Delta E_F + e \cdot U_{ex}\right)\right)^{1/2}$$

Now let's look at the various *currents* flowing in the conduction and valence bands without an external voltage.

- We know that the net current is zero – we are in an equilibrium condition as long as we do not apply an external voltage (or shine some light on it).
- We also know that we have a dynamic equilibrium as in the case of the recombination/generation business before. The net current is zero because the local currents cancel each other. This implies that the electron current flowing uphill (from left to right) is identical in magnitude and opposite in sign to the one flowing from right to left (downhill).
- The same reasoning applies, of course, to the holes in the valence band.

The partial currents discerned above have several specific names. The current component *flowing uphill in energy* is called . . .

- **Diffusion current**, because the driving force behind this current is the density gradient in the carrier density. This always leads to a current component given by Fick's first law to

$$j_{Diff} = -D\, e\, \nabla n$$

- With n = density of the carriers in question. (The electric charge **e** has to be given explicitly in this equation because n only gives the number of particles present.)
- It is also alternatively called **recombination current** because all the electrons (or holes) flowing to the other side become excess minority carriers there and must disappear by recombination, which can be depicted as a current flowing between the bands.
- Looking a little ahead, a **p–n** junction is a diode and currents in diodes are classified as either forward or reverse current. Well, the current component in question here is responsible for the **forward current** in the diode and therefore is also addressed under that name. We will use mostly this name and abbreviate this current component with j_F.

The partial current *flowing downhill in energy* is called . . .

- **Field current**, because it is the current that the electrical field in the junction produces; i.e. the carriers flow in the general direction of the field lines with the respective proper signs. The diffusion current, in contrast, flows against the force exerted by the field (which will slow down these carriers!)

- **Drift current**, because it is the current that results from a drift – caused by the electrical field – superimposed on random diffusion movements.
- **Generation current**, because the (minority) carriers that were swept down the energy hill (or up in the case of the holes) get replaced by increased generation, thereby keeping the density constant.
- **Reverse current** in the diode nomenclature explained above. We will use mostly this name and abbreviate this current component with j_R.

Simple Current–Voltage Characteristics

In equilibrium, without an external voltage U_{ex} and without illumination, we know that the net current is zero, or

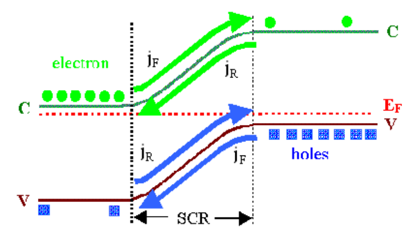
- $j_F = -j_R$, or, to be more precise,

$$j_F(U_{ex}=0) \;=\; -\,j_R(U_{ex}=0)$$

To make life a little easier, we now drop some matter-of-course indices, *and the signs*; i.e. we only look at the *magnitudes of the current components*. It is easy enough to sort out the signs in the end again; in case of doubt refer to the link. In this shorthand notation we have

$$j_F(0) \;=\; j_R(0)$$

- If we draw these currents schematically into the band diagram from above, it looks like this:

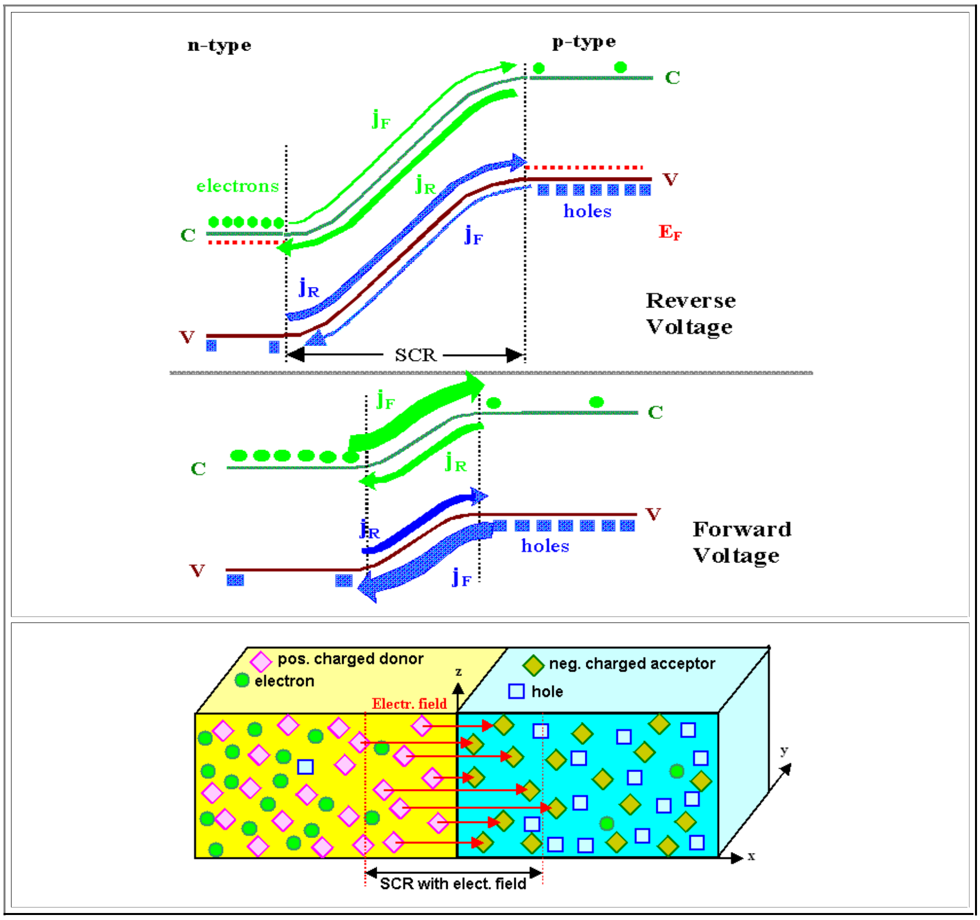


- Of course, the currents do not flow on both sides of the band edge; this is simply a drawing means.

What happens for finite external voltages? First let's look at the band diagrams:

- An external potential U_{ex} is added, which will raise or lower the equilibrium potential, depending on its sign; for sake of simplicity we only move the **p**-side band diagram. But do we have to move it up or down?
- It depends: We have two possibilities for choosing the polarity of the external voltage, either increasing the already existing electrical field or weakening it. (Remember that the field lines are pointing from the **n**-side to the **p**-side; if you have forgotten why this is so, look again at the explanation given above.)
- Thus, the potential on the **p**-side goes *up* for the negative pole of the voltage supply on the **p**-side (always think about if electrons are repelled or attracted if you are unsure about how a potential moves bands), and *down* for the positive pole on the **p**-side.
- We no longer have an equilibrium situation – the Fermi energy is no longer the same everywhere; we must leave it undefined across the junction. (Later on we will have a look at how the Fermi energy behaves inside the **SCR**.)
- Far away from the junction, however, nothing (or very little) has changed. We still may consider these parts of the semiconductor to be in equilibrium (or at least very close to it).

The band diagram for the two possible basic cases then look like this:



- The diffusion currents are shown increased (thicker arrow) if the energy barrier was lowered, and decreased if it was raised. The drift currents are unchanged.

The situation now is rather simple. The potential step is either increased or decreased. Let's first look what happens to the *forward currents* $j_F(U_{ex})$.

- At zero volts the electron and hole forward currents have a certain value that is certainly determined by the height of the energy barrier that the carriers have to overcome, following *Boltzmann statistics* (as an approximation to the Fermi statistics, of course).
- In other words, the equation for this current includes an **exp[–*E*/(k*T*)]** term. Changing the energy barrier ***E*** by Δ ***E*** simply means to multiply the current at zero volts with **exp[–Δ*E*/(k*T*)]**.
- Since the magnitude of j_F for zero external voltage is just $j_R(U_{ex}=0)$, the forward current current $j_F(U_{ex})$ at *any* voltage U_{ex} is (and this is true both for the electron and the hole forward current)

$$j_F(U_{ex}) \;=\; j_R(U_{ex}=0)\cdot\exp\left(-\frac{\Delta E}{kT}\right) \;=\; j_R(U_{ex}=0)\cdot\exp\left(-\frac{e\cdot U_{ex}}{kT}\right)$$

- Note that, due to the minus sign in the exponent (which we inherited from the Boltzmann distribution), increasing the energy barrier leads to a decrease of the forward current; we will come back to this later.
- Imagine this as a lot of (drunken) bicyclists with various random momentums driving around randomly at the foot of a hill. Some of them on occasion will make it up the hill because their momentum was large enough and they were heading in the right direction. The fraction of bicyclists making it will simply change exponentially with the Boltzmann factor relative to their "current" at some reference value if the hill is raised or lowered.

Now to the *reverse current* $j_R(U_{ex})$.

- It corresponds to (drunken = randomly moving) bicyclists that drive around for a certain time (corresponding to the life time of the minority carriers) on the plateau on top of the hill before falling off their bikes (recombining).
- However, everybody who by accident makes it to the edge of the hill will invariably careen down, i.e., produce a reverse current.
- Clearly, it only matters how many carriers happen to make it to the edge of the potential drop, not how deep it is. In other words: *The reverse current does not depend on the external voltage*, or

$$j_R(U_{ex}) \;=\; j_R(U_{ex}=0) \;=\; j_R$$

The *total current* is simply the *difference* between forward and reverse current for the electrons and the holes, so we have

$$j(U_{ex}) = \left(j_F(U_{ex}) - j_R\right)_e + \left(j_F(U_{ex}) - j_R\right)_h$$

$$j(U_{ex}) = \left(j_R{}^e + j_R{}^h\right) \cdot \left(\exp\left(-\frac{e \cdot U_{ex}}{kT}\right) - 1\right)$$

- Note that we did *not* assume that the forward or reverse current of the holes must be identical to the forward or reverse current of the electrons, respectively. Of course, if everything were symmetrical, we would have $j_R{}^e = j_R{}^h$, but we want to keep it a as general as possible even at that level since many real devices employ wildly different electron and hole currents across the junction.

This is the famous **diode equation**, and this is all there is to it for straight-forward **p–n** junctions – except that the technically relevant diode voltage U_D, being related to the technical current flow direction, is taken as *positive* for the current flowing in *forward* direction; thus, we have $U_D = -U_{ex}$.

- This just means that, in order to make the forward current flowing, the external voltage must be applied such that it effectively reduces the built-in potential difference.

Combining the reverse currents of electrons and holes in a single constant $j_0 := j_R{}^e + j_R{}^h$, we arrive at the final form of the ideal diode equation:

$$j(U_D) = j_0 \cdot \left(\exp\left(\frac{e \cdot U_D}{kT}\right) - 1\right)$$

All that is left to do is to consider the reverse currents j_0 a bit more closely.

- Thinking again about drunken bicyclists, but now driving around on the top of the hill (and thus representing electrons), we might be tempted to assume that $j_R{}^e$ should be *proportional to their numbers*, i.e., to the minority carrier *density* on the plateau.

This, however, is *wrong*.

- So let's sober up and think a bit harder: You only can extract the bicyclists *once*! Yet if you want a *constant* current over time, the best you can do is to take all carriers for the current that are *(i) generated per time unit and (ii) making it to the edge*.
- In other words, you *need to refill the ranks of bicyclists* and the current will be *proportional to the generation rate* ***G*** (to what comes out of the bars per time interval), which we know is equal to the *recombination rate* ***R*** in undisturbed semiconductors and given by

$$G = R = \frac{n_{min}}{\tau} = \frac{n_i{}^2}{\tau \cdot N_{Dop}}$$

- With τ = lifetime.

Thinking a bit harder yet, we realize that minority carriers generated way back from the junctions will not contribute to the current. They will "fall off their bike" (recombine) long before they have a chance to come close to the drop-off. Obviously we only must consider carriers within a certain distance of the junction, and this distance is, of course, the *diffusion length* ***L***.

- This gives us

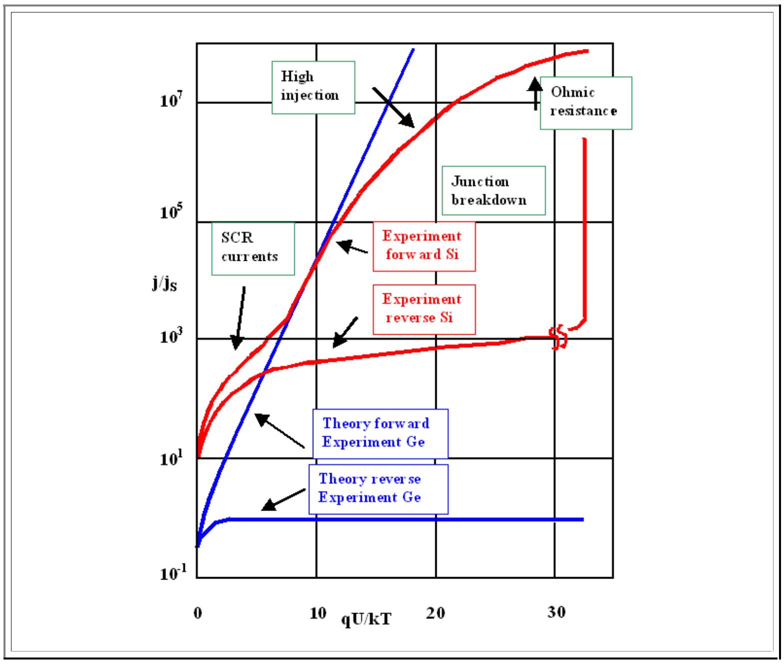
$$j_R = \text{const.} \cdot e \cdot L \cdot G = \frac{\text{const.} \cdot e \cdot L \cdot n_{min}}{\tau} = \frac{\text{const.} \cdot e \cdot L \cdot n_i{}^2}{\tau \cdot N_{Dop}}$$

- The elementary charge **e** is needed to make an electrical current out of a particle current. And as it turns out by more involved calculations, the *proportionality constant is = 1*.

This gives us the complete diode equation exclusively in terms of *primary material properties*:

$$j(U_D) = \left(\frac{e \cdot L \cdot n_i{}^2}{\tau \cdot N_A}\left(\exp\left(\frac{e \cdot U_D}{kT}\right) - 1\right)\right)_{\text{electrons}} + \left(\frac{e \cdot L \cdot n_i{}^2}{\tau \cdot N_D}\left(\exp\left(\frac{e \cdot U_D}{kT}\right) - 1\right)\right)_{\text{holes}}$$

- This is a remarkable achievement – obtained without involved calculations and cutting corners only once (**proportionality const. = 1**). *But how good is it*? Only the experiment can tell.
  - If we measure the current–voltage characteristic of an "ideal" **p–n** junction, we will find the following curves:



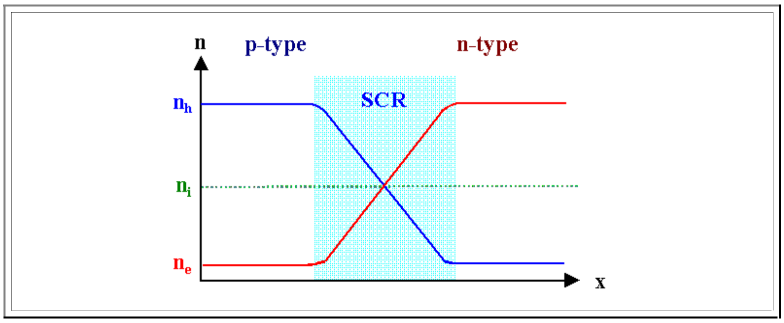
  - Generally, for **Ge** (or other semiconductors with relatively small band gaps) the measured characteristics is remarkably close to the one predicted by our formula. For **Si**, however (and other semiconductors with large band gaps), *it is not a good formula*, particularly for for the reverse current. We have large deviations from theory, labeled with black lettering. So, let's see what went wrong (more details in the link) in each case.
- ***First***, our theory has the usual (trivial) omissions. We did not include any ohmic resistance which can be easily added by putting a resistor in series to the junction. The result is the ohmic behavior for larger voltages as seen at larger currents.
- ***Second***, everything will break down at high field strength; this is true for a junction, too. So for large reverse voltages (easily in the range **100 V . . . 1,000 V**), the junction will go up in smoke while drawing a large current called "junction breakdown".
  - While these points would apply to a **Ge** junction too (they are not shown in the ideal characteristics), the remaining deviations for **Si** involve a major oversight in our present theory:
- ***Third:*** **We did not include carrier generation (and recombination) in the space charge region!**
  - In the bicyclist picture, we did not take into account that there are bars along the slope of the hill, too, which will emit bicyclists with a certain momentum and direction – they may either go up or down the hill and thus add to the current of particles moving in either direction.
  - This adds four more current components (forward and reverse for holes and electrons) summarily called **generation currents from the SCR**.
- How large are these **SCR**-caused current components?
  - The answer comes from one of the more involved problems in semiconductor physics, it is not easy to obtain for real semiconductors (we will do it later). However, there is an *easy way of thinking about it* that even comes up with the usual given formula resulting from serious (but still approximate) computing. But we sure will have to cut a few corners!
  - Here we go:

Current–Voltage Characteristics with Generation Currents from the Space Charge Region

- We know the maximum current j_{max} that could emerge from the space charge region: It is the generation rate of carriers times the width of the **SCR** in complete analogy to the discussion above. More than that cannot flow out (in one direction for the maximum) per unit time.
  - Every generation event produces a hole and an electron, so we have

$$\boxed{j_{max} \;=\; 2e \cdot G_{SCR} \cdot d}$$

  - With d = width of the **SCR**, and G_{SCR} = generation rate inside the space charge region.
- How large is G_{SCR}? This needs to be considered in detail since it wouldn't help to simply use the known equation $G = n_{min}/\tau$, because n_{min} is *not constant* across the **SCR**; *very schematically*, it rather looks like this:



Inside the **SCR**, this makes ***G*** a strong function of ***x*** – how are we going to handle this?

- Well, let's take a kind of *average value* for the carrier density, and what suggests itself is the *intrinsic carrier density* n_i, which is the value at the point where the two curves cross each other because of the mass action law stating $n_e \cdot n_h = n_i^2$.
- Within this (questionable!) approximation the maximum current generated in the **SCR** then becomes

$$j_{max} = \frac{2e \cdot n_i \cdot d}{\tau}$$

And we know more: If the external voltage is zero, the total current is zero and this means that half of the **SCR** current must be forward and the other half reverse. We have

$$j_F(0) = j_R(0) = \frac{e \cdot n_i \cdot d}{\tau}$$

If we now change the barrier height by eU_{ex}, the forward current will change as before. However, we cannot simply multiply by $\exp[-eU_{ex}/(kT)]$ as before!

- While a carrier generated at the bottom of the hill experiences the full added potential, a carrier generated further up sees less or even no potential if it originates all the way uphill.
- So again, let's be sloppy and assume an *average additional energy barrier*, average between everything and nothing – and this will be $eU_{ex}/2$.
- Again assuming that j_R does not depend on the *barrier height* (but slightly on ***U*** since the width ***d*** of the **SCR** is voltage dependent), this gives us:

$$j_F(U_{ex}) = \frac{e \cdot n_i \cdot d}{\tau} \cdot \exp\left(-\frac{eU_{ex}}{2kT}\right)$$

$$j_R = \frac{e \cdot n_i \cdot d}{\tau}$$

- The two components no longer add up to j_{max}, but we don't have to worry about this. We only would be very wrong for *large* forward currents, but in this case the *bulk* forward current is always much larger anyway – so it does not really matter much for the diode behavior.

The total current from the space charge region then becomes $j_{SCR} = j_F - j_R$. Written out and, as above, using $U_D = -U_{ex}$, we have

$$j_{SCR}(U_D) = \frac{e \cdot n_i \cdot d}{\tau} \cdot \left(\exp\left(\frac{eU_D}{2kT}\right) - 1\right)$$

- This happens to be *exactly the same formula* (give or take a factor of **2**) *that we would obtain with the "proper" theory*.

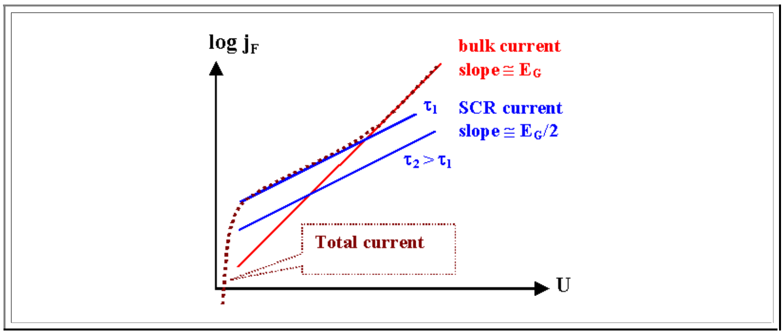
- We now can write down the diode equation in all its splendor:

$$j_{\text{total}}(U_D) = \underbrace{\frac{e \cdot L \cdot n_i^2}{\tau \cdot N_A}\left(\exp\left(\frac{eU_D}{kT}\right) - 1\right)}_{\text{e}^- \text{ bulk}} + \underbrace{\frac{e \cdot L \cdot n_i^2}{\tau \cdot N_D}\left(\exp\left(\frac{eU_D}{kT}\right) - 1\right)}_{\text{h}^+ \text{ bulk}} + \underbrace{\frac{e \cdot n_i \cdot d}{\tau}\left(\exp\left(\frac{eU_D}{2kT}\right) - 1\right)}_{\text{h}^+,\ \text{e}^- \text{ SCR}}$$

  - We may use the same abbreviation for the bulk reverse current as above and additionally abbreviate the SCR one in a similar manner, then we see more clearly that we effectively have two diodes parallel, the first (prefactor j_{01}) representing the bulk currents and the second (prefactor j_{02}) representing the SCR currents:

$$j(U_D) = j_{01} \cdot \left(\exp\left(\frac{e \cdot U_D}{kT}\right) - 1\right) + j_{02} \cdot \left(\exp\left(\frac{e \cdot U_D}{2kT}\right) - 1\right)$$

- Let's see what it means in forward direction:
  - We may neglect the **–1** in the **SCR** part of the forward current; it then adds a component that increases with **exp[eU_D / (2kT)]**, i.e., with *half the slope* of the bulk current (in an Arrhenius diagram). The half-slope component will always "win" at small voltages but pale to insignificance at higher voltages as shown in the illustration:



  - The combined characteristic looks very much like the measured behavior shown above; the sharp drop of the current close to U **= 0 V** is due to the **–1** in the diode equation (i.e., the reverse current j_R) which we neglected for larger voltages.
  - We also see that the exact value of the **SCR** forward current indeed only matters for small voltages, as claimed above.
- What do we get in *reverse direction*?
  - First, *the reverse current now is voltage dependent* because the width of the space charge region and thus j_R increases with a $U^{1/2}$ law.
  - Second, the *total reverse current now is larger*. Assuming a symmetric junction ($N_D = N_A = N_{Dop}$) and identical life times (and so on) for electrons and holes, it is easy to calculate the relation **j_R(bulk) / j_R(SCR)**; we have

$$\frac{j_R(\text{bulk})}{j_R(\text{SCR})} = \frac{\dfrac{e \cdot L \cdot n_i^{\,2}}{\tau \cdot N_{Dop}}}{\dfrac{e \cdot d \cdot n_i}{\tau}} = \frac{L \cdot n_i}{N_{Dop} \cdot d}$$

- The decisive factor is n_i. It decreases exponentially with increasing band gap E_g.
  - This answers the question why **Ge** junctions follow the simple theory, while **Si** junctions are far off: If $n_i \gg N_{Dop}$, then **j_R(bulk) >> j_R(SCR)** and the **SCR** contribution will not be felt.
  - The generation current from the **SCR** thus is much more important in semiconductors with larger band gaps. The characteristics from above show this rather clearly.
  - Whereas the **SCR** part may be safely neglected for **Ge** (E_g **= 0.6 eV**), it is about (**10^2 . . . 10^3**) times larger than the bulk diffusion current in **Si**.
  - The **SCR** currents should be *absolutely dominating* in large band-gap semiconductors. Not only is n_i rather small, but **$L = (D\tau)^{1/2}$** is very small, too, since these materials are often direct semiconductors.