Semiconductor Devices: the p-n junction

1. The Fermi energy level (μ)

As mentioned in the last part on thermoelectric effects, the Fermi energy level plays a very important part in semiconductor devices, especially in junctions between different semiconductors and between semiconductors and metals. To review**, the definition of the Fermi energy level, μ** (sometimes called the chemical potential)**, is that the Fermi level is the energy level that has a 50% chance of being filled. All levels above μ have less than 50% chance of being filled, and all levels below it have a greater than 50% chance of being filled:**

$$f(\varepsilon,T) \;=\; 1 / [e^{(\varepsilon-\mu)/kT} + 1] \quad ; \quad \text{so } f(\varepsilon=\mu,T) = \tfrac{1}{2} .$$

If the Fermi levels of two different semiconductors are initially different, then when they are joined at a junction the electrons in the semiconductor with the higher Fermi level will naturally move over and fall down to the lower states in the other semiconductor. But the added electrons will create a negative voltage, and hence create for the electrons in the lower material a positive potential energy that will raise up the level of the lower Fermi level; and the absence of the electrons in the higher Fermi level material will decrease the level of the higher Fermi level until the two materials have the same Fermi level. This analysis has assumed equilibrium without any voltage or temperature differences between the two materials.

2. The Fermi level in intrinsic, n-type and p-type semiconductors

At T=0K, the Fermi level in an intrinsic semiconductor (undoped) is half way between the valence and conduction bands: $\mu = \tfrac{1}{2}E_{gap}$ if we measure ε=0 at the top of the valence band. We obtained this result previously when we considered intrinsic semiconductors. That analysis also indicated that as the temperature increases, the μ will increase slightly. [Recall that in the **Intrinsic** section under Chemical potential we obtained the relation:

$$\mu \;=\; \tfrac{1}{2}E_{gap} + (3/4)k_BT\ln(m^*_h/m^*_e) ,$$

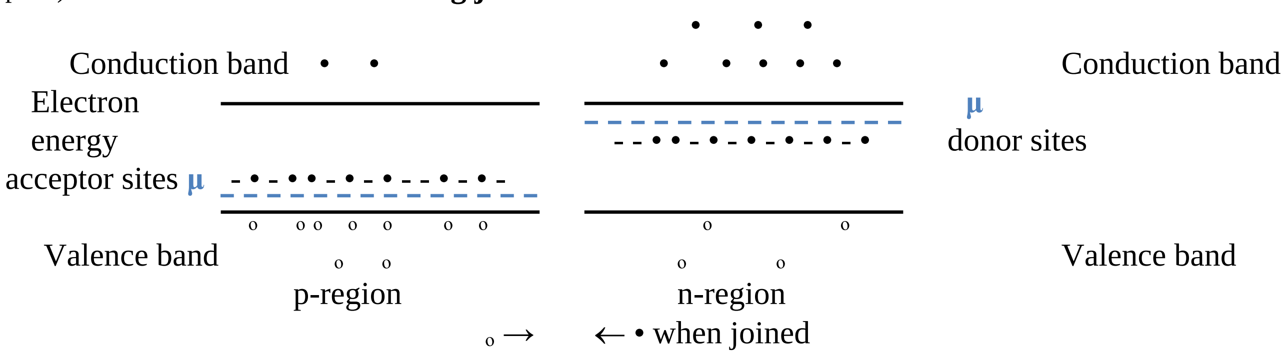
and that generally m^*_h is slightly larger than m^*_e for an intrinsic semiconductor (no doping).] This makes sense since at T=0K all the electrons in the semiconductor are in the valence band [$f(\varepsilon<\mu,0)=1$] and no electrons are in the conduction band [$f(\varepsilon>\mu,0)=0$]. As the temperature increases, some of the valence electrons jump up to the conduction band. This will tend to move the position of $f = \tfrac{1}{2}$ up in energy.

For n-type semiconductors at T=0K, we have **donor** energy levels that are **filled** and are very close but slightly less than the bottom of the conduction band. Thus the Fermi energy level (f=½) should be above the filled donor levels (f=1) but underneath the empty conduction band (f=0). As T increases, the μ will decrease slightly since the donor levels will start being vacated (f<1). For low doping levels, μ will approach ½ of the energy gap between donor level and the conduction band rather quickly as the temperature increases; for higher doping levels, μ will approach ½ of the energy gap between the donor level and conduction band much more slowly with increasing temperature. Due to electrons falling back down to open donor levels as well as moving up, the fraction of donor levels filled will still be > ½ .

For p-type semiconductors at T=0K, we have **acceptor** energy levels that are **unfilled** and are very close but slightly above the top of the valence band. Thus the Fermi energy level (f=½) should be between the filled valence band (f=1) and the unfilled acceptor levels (f=0). As temperature increases, the μ should increase slightly since the acceptor levels will start filling up (f>0). For low doping levels, μ should approach ½ of the gap between the valence band and the acceptor level rather quickly with increasing temperature; for high doping levels, μ will approach the ½ point much more slowly with increasing temperature.

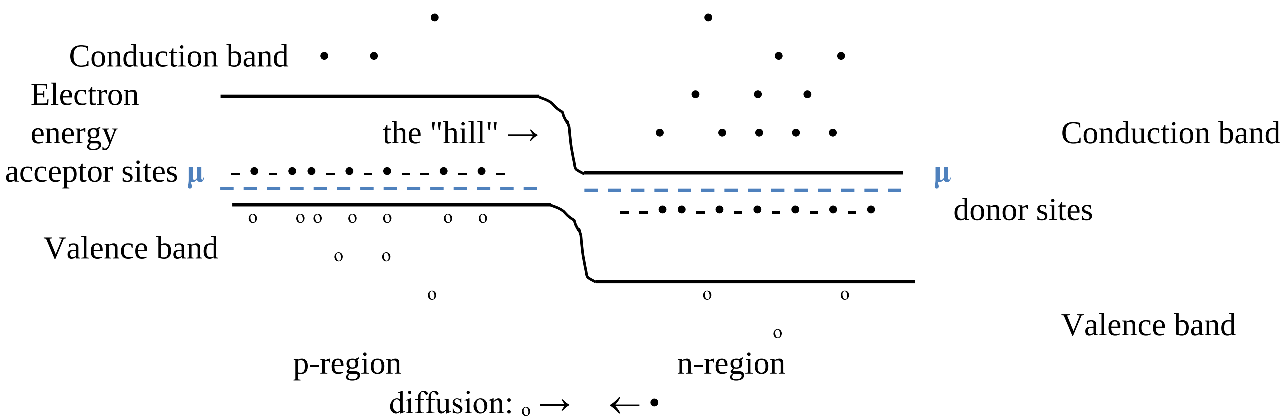
3. Unbiased p-n junction

We will now employ an **energy versus distance** diagram (NOT energy vs wavevector (ε vs k) as we have done in the past!). **Before being joined:**



We will show on one side the p-type semiconductor, then in the middle we'll have the junction, and then on the other side we'll have the n-type semiconductor. The energy axis will indicate the energy of the electrons. Hence **electrons • will tend to go downhill** while **holes o ,** which have an opposite charge, **will tend to go uphill**. Note from the above discussion that the conduction and valence bands will have to be shifted in energy in the two semiconductors over the junction since the Fermi levels must match:

UNBIASED JUNCTION (no applied voltage across)



electron flow: → ←

thermal **recombination** net current flow =0

Since for the same basic semiconductor (undoped) the conduction bands should have been at the same energy and the μ from the n-region was initially higher than the μ from the p-region, therefore electrons from the n-region diffused over to the p-region raising the μ in the p-region and lowering the μ in the n-region until the μ's matched. The added electrons in the p-region and the absence of electrons in the n-region creates a capacitor-like effect.

In this case, there are two competing effects that balance one another out. We have electrons in the valence band of the p region jump up to the conduction band due to the thermal energy, and then they will have a tendency to fall down the hill toward the n-region. This movement of electrons from the p-region to the n-region and is called the **thermal current**. (The thermal energy will also tend to cause electrons to jump up in the n-region, but they will not naturally fall up to the p-region.)

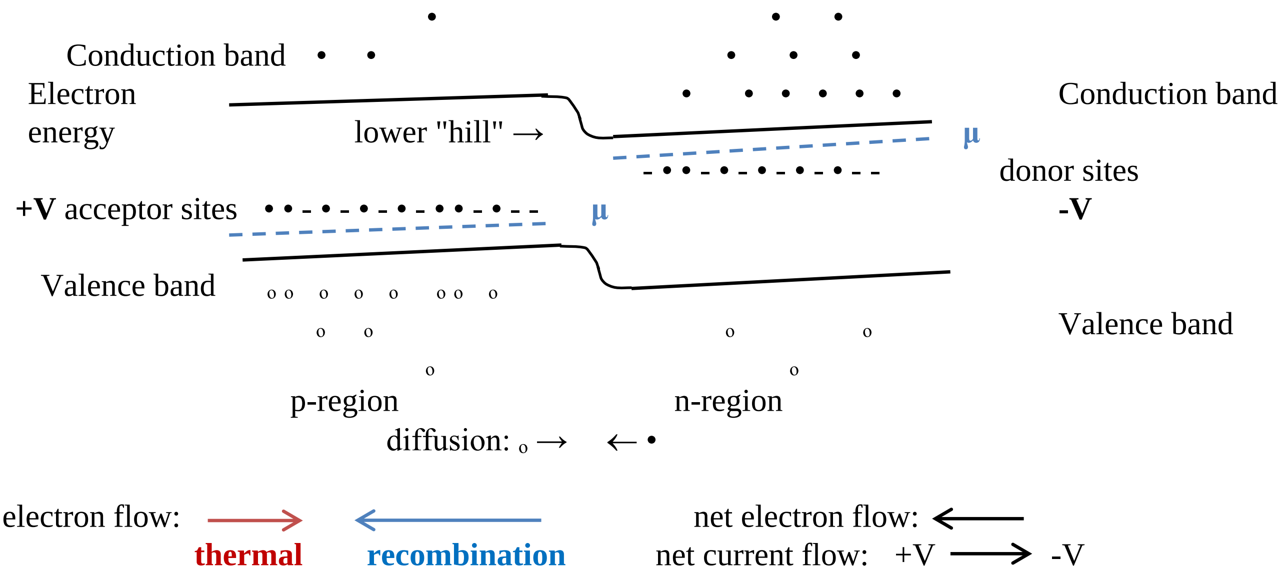
The second effect is due to the higher number of electrons in the conduction band of the n-region. Since there are a larger number of electrons in an n-type semiconductor, there will be a tendency for a few of these electrons to **diffuse** over to the p-type side even though they must go uphill to do it. Once over to the p-side, these electrons will tend to fall down to some of the many holes in the p-side. This results in a movement of electrons toward the p-side and is called the **recombination current**.

Note that the two currents, the thermal current and the recombination current, are in opposite directions. These two currents in the unbiased situation will exactly cancel one another so that there will be no net current in the unbiased situation.

4. Forward bias at a p-n junction

If we apply a **positive voltage to the p-side** (and hence a negative voltage to the n-side), we will cause a shift in the energy diagram. Since electrons are negative charged particles, the electron energy will decrease if we apply a positive voltage, and will increase if we apply a negative voltage. Hence we get the following energy-space diagram: Note: the donor and acceptor sites should be slanted also, but that was hard for me to do.

FORWARD BIASED JUNCTION (+V applied on p side)



We first note that electrons will tend to slide down (from right to left) in potential energy, and the holes will tend to float up (from left to right) - which means the electrons in the valence band are moving down and to the left to fill the holes. Near the junction, electrons in the conduction band falling down from the left will tend to fall down into the holes in the valence which are moving up and to the right. This is called the recombination current.

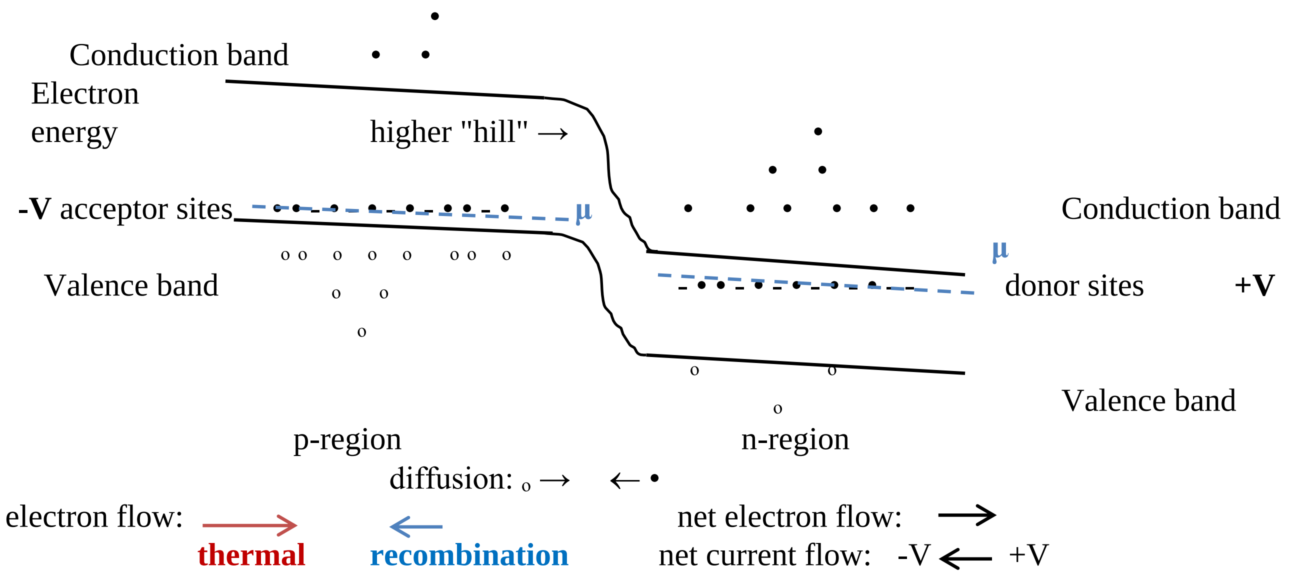
We then note that **the "hill" is not as high**. This results in a change in the relative amounts of the thermal and recombination currents. The thermal current was generated by the thermal energy, and should not depend on the hill height. Thus the **thermal current should remain unchanged** by the forward bias. The recombination current, however, should be influenced by the height of the hill. It will be much easier for the electrons to go up a smaller hill, and so the **recombination current should increase by a relatively large amount**.

Therefore the net current should have a relatively **LARGE number** of electrons flowing toward the p-side (the high voltage side) since the net current consists of the thermal current (electrons going toward the n-region which hasn't changed) and the recombination current (electrons going toward the p-region which has increased by a large amount). Note that electrons flowing toward the high voltage side means that the normal current (flow of positive charge) is from the high voltage side to the low voltage side.

5. Reverse bias at a p-n junction

If we apply a negative voltage to the p-side (and hence a positive voltage to the n-side), we will again cause a shift in the energy diagram. Since electrons are negative charged particles, the electron energy will increase if we apply a negative voltage, and will decrease if we apply a positive voltage. Hence we get the following energy-space diagram: Note: the donor and acceptor sites should be slanted also, but that was hard for me to do.

REVERSE BIASED JUNCTION (+V applied on n side)



We first note that the electrons will tend to slide down in potential energy and so tend to go down and to the right, and the holes will tend to move up and so tend to go up and to the left.

We then note that **the "hill" is now higher**. This again results in a change in the relative amounts of the two currents. The **thermal current** was generated by the thermal energy, and the thermal electrons naturally fall down the hill. As before this **should not depend on the hill height**. Thus the thermal current should remain unchanged by the reverse bias. The recombination current, however, should be influenced by the height of the hill. It will be **much harder for the electrons to go up a large hill, and so the recombination current should decrease**.

Therefore the net current should have a relatively **SMALL number** of electrons flowing toward the n-side (the high voltage side) since the net current consists of the thermal current (electrons going toward the n-region which hasn't changed) and the recombination current (electrons going toward the p-region which has decreased). Note that electrons flowing toward the high voltage side means that the normal current (flow of positive charge) is from the high voltage side to the low voltage side.

A second effect is that as the electrons fall to the right and holes rise to the left, **there will now be very few electrons or holes in the region of the junction**. This will be the important aspect when we talk about MOSFETs.

6) A more quantitative analysis

The thermal current depends on T but not on the biasing voltage. Therefore for circuit behavior, **$I_{thermal} = I_o$ = constant**.

The recombination current does depend on V. Using the Boltzmann probability distribution, the probability of an electron climbing a hill (a potential energy "hill" of energy eΔV, where ΔV is the voltage difference across the p-n junction) is:

$P(\varepsilon) = A\,e^{-\varepsilon/kT}$, so $I_{recomb} = I_o\,e^{+e\Delta V/kt}$.

Recall that the charge of the electron is negative, hence the plus sign in the recombination's exponent.
Also note that any base energy point that we call ε=0 can be incorporated into the I_o since $e^{(-\varepsilon+e\Delta V)/kt} = e^{-\varepsilon/kT}\,e^{+e\Delta V/kt}$ and the $e^{-\varepsilon/kT}$ is a constant that can go into the I_o .

With **no biasing** voltage:

$$I_{recomb} = I_{thermal} = I_o, \quad \text{and} \quad I_{net} = I_{recomb} - I_{thermal} = 0.$$

With a **forward biasing** voltage (ΔV is positive for the electron):

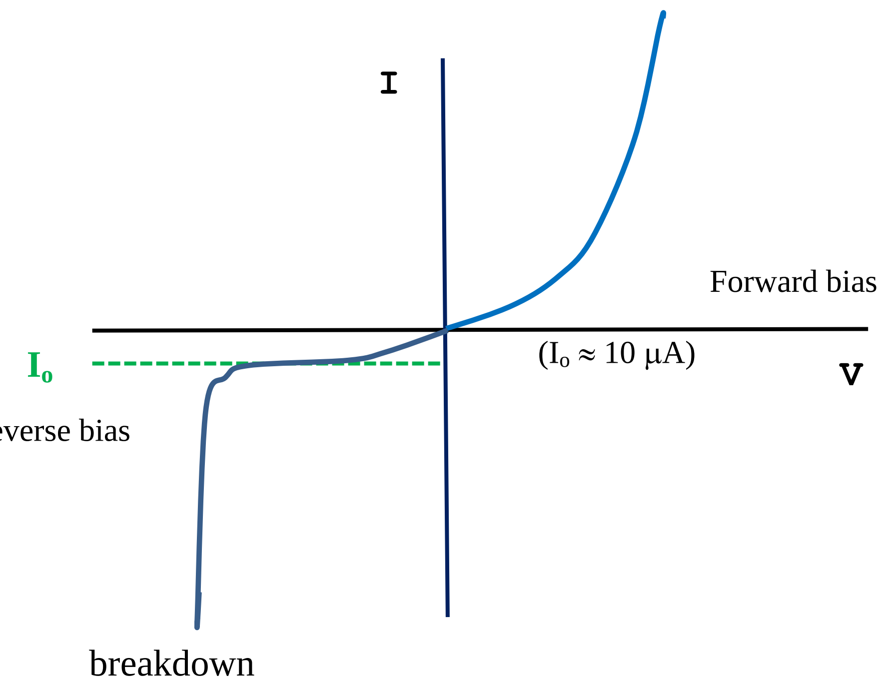
$$I_{recomb} = I_o\,e^{+e\Delta V/kT}, \quad \text{and} \quad I_{net} = I_{recomb} - I_{thermal} = I_o\,(e^{e\Delta V/kT} - 1)$$

and so the recombination current increases exponentially with ΔV.
For a **reverse bias** voltage, ΔV is negative and the recombination current decreases exponentially to zero. Thus we can look at the net current:

$$I_{net} = I_{thermal} - I_{recomb} = -\,I_o\,(1 - e^{e\Delta V/kT}) \quad \text{where the } \Delta V < 0.$$

The negative on the current in the reverse bias reflects the fact that the applied voltage is negative and the current is negative.

Overall, $I_{net} = I_{recomb} - I_{thermal} = I_o\,(e^{e\Delta V/kT} - 1)$. If we graph the current, I, versus voltage, V, curve for this p-n junction, we get something a lot different than Ohm's Law (I = V/R):



If we have too high of a reverse bias, then we can accelerate some of the electrons so high they knock valence electrons out of the valence band, and then these electrons can knock others out, and so on just like an avalanche of rocks or snow. This is not good for the material and should normally be avoided. (Note: zener diodes have a reverse bias "**breakdown**" that is utilized in some circuits, but this breakdown is somewhat different than what we have indicated above. We will consider the Zener diode behavior later.)