# DIODES

1. Tunnel diodes
2. Zener diodes
3. Photo diodes
4. LED's (light emitting diodes)

## 1) Tunnel diodes

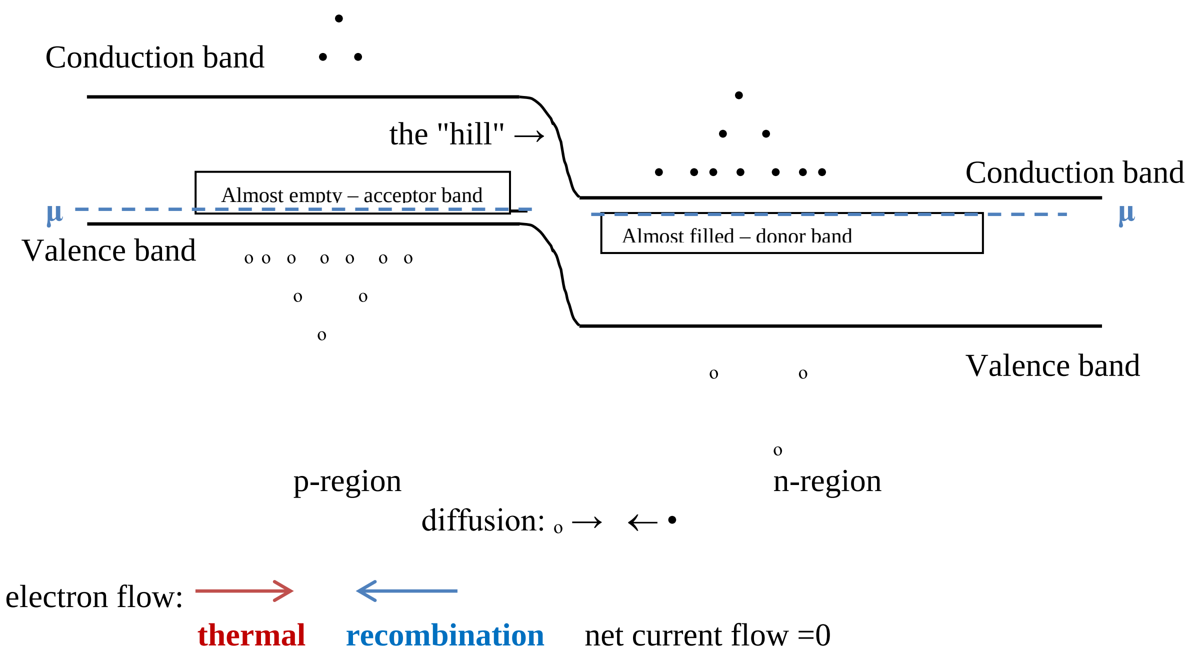
A tunnel diode has a really strange I vs V relationship. This is caused by a quantum mechanical phenomena called **tunneling** which has no classical equivalent. The closest thing classically is the idea of tunneling through a barrier instead of going over the top of the barrier. The basic idea of tunneling is that if a permitted energy state at one place is separated from a permitted energy state at another place by a spatial gap that does not permit that energy, then a particle can go from one place to the other (crossing the "forbidden gap") with a probability that depends on the spatial size of the gap as well as the energy height needed to conventionally jump over the gap.

Remember that we have the wave/particle duality for matter just like we have for light. A wave that hits an absorbing material will actually penetrate a bit as it is being absorbed. Similarly, an electron wave (remember that the wavefunction, $\Psi$, is related to the probability of finding the electron) may penetrate a barrier a bit.

What is needed for this diode is for both the p-type and the n-type material to be heavily doped and for the separation between the two types (the transition region) to be very narrow. In the p-type, the **heavy doping** causes the acceptor levels to **overlap and form a band** that adds empty levels to the valence band. In the n-type, the heavy doping causes the donor levels to form bands that add filled levels to the conduction band. These doping atoms are so close together due to the heavy doping that the electrons are no longer localized so they form a band in the material rather than isolated levels. Electrons in these bands can then belong to the whole solid and move through the solid rather than being stuck to individual atoms.

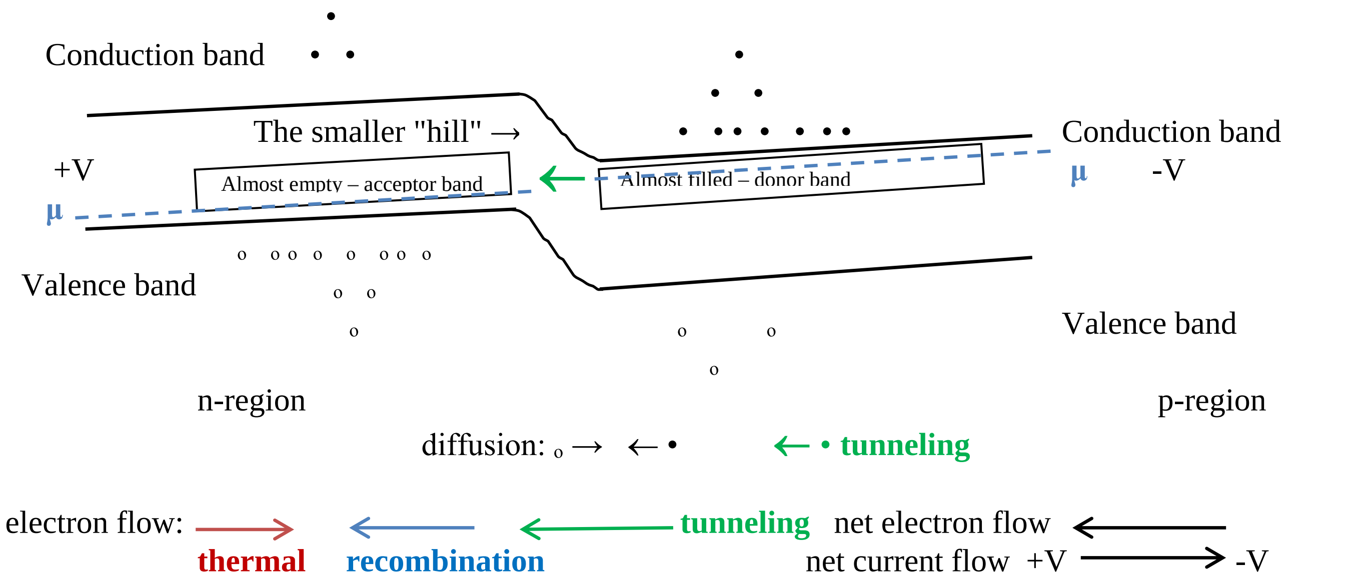
For the unbiased case, the **energy-distance** diagram looks like the following:

**UNBIASED JUNCTION (V=0, I=0) at low T**



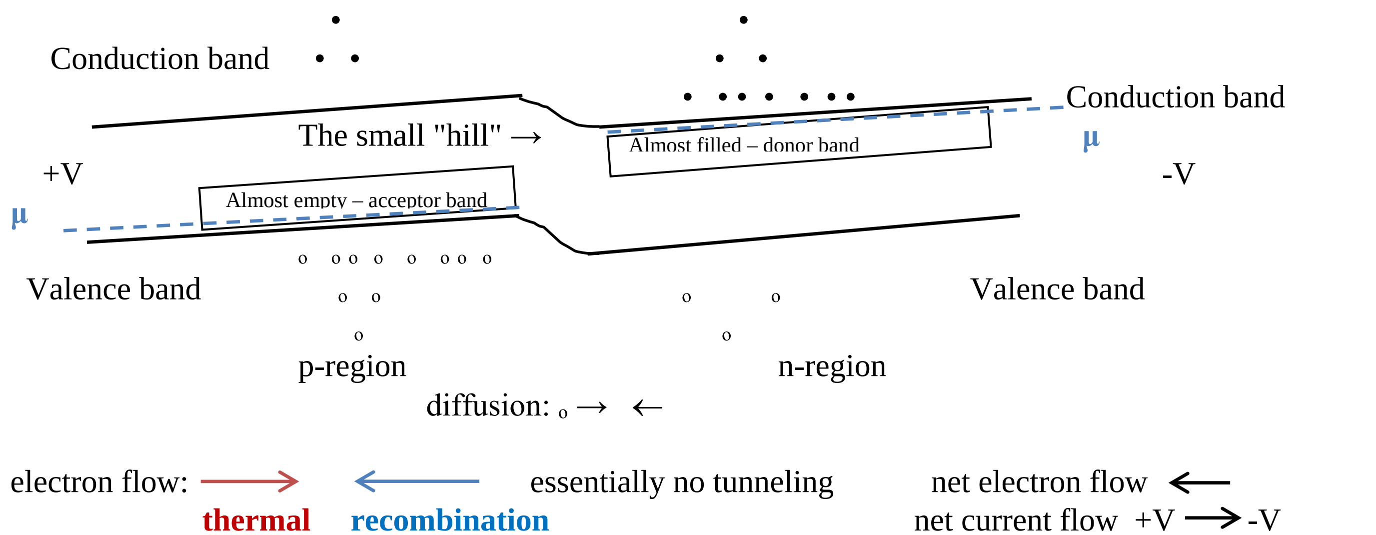
As we add forward bias, we get the following situation: the p-side electron energies are slightly lower, the n-side electron energies are slightly higher. This allows the electrons in the valence band in the n-side to tunnel over to the partially empty acceptor band on the p side, which moves electrons towards the +V side and so increases the current, I. This tunneling increases the current more than the normal forward bias increases current due to diffusion due to reduced hill height.

**Slightly FORWARD BIASED JUNCTION (V>0, I>0)**

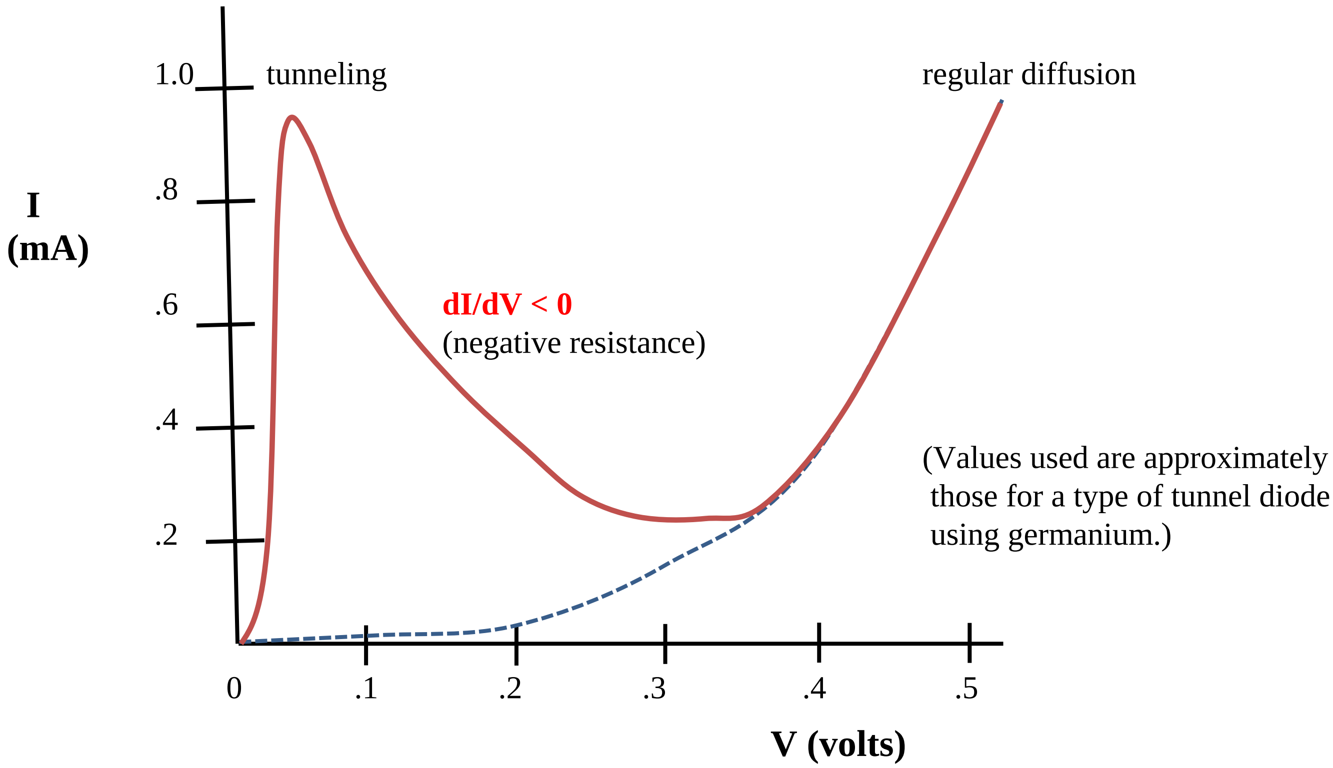



As the voltage is increased further, we get this situation: the p-side is slightly lower than it was, the n-side is slightly higher than it was; net effect is to reduce tunneling while increasing diffusion. The reduction in tunneling is greater than the increase in diffusion so the current goes DOWN with increasing voltage!

**More FORWARD BIASED JUNCTION (V>0, I>0)**



We now plot the current vs voltage relationship for this tunnel diode (solid line), and compare it to the regular pn junction (dotted line). Values used are approximately those for a tunnel diode using germanium.




Note that in the region between the tunneling peak and the regular diffusion increase, the I vs V curve goes **down**, which corresponds to a negative slope which corresponds to a negative resistance (V = IR, so [1/R] is the slope of the I vs V curve!).

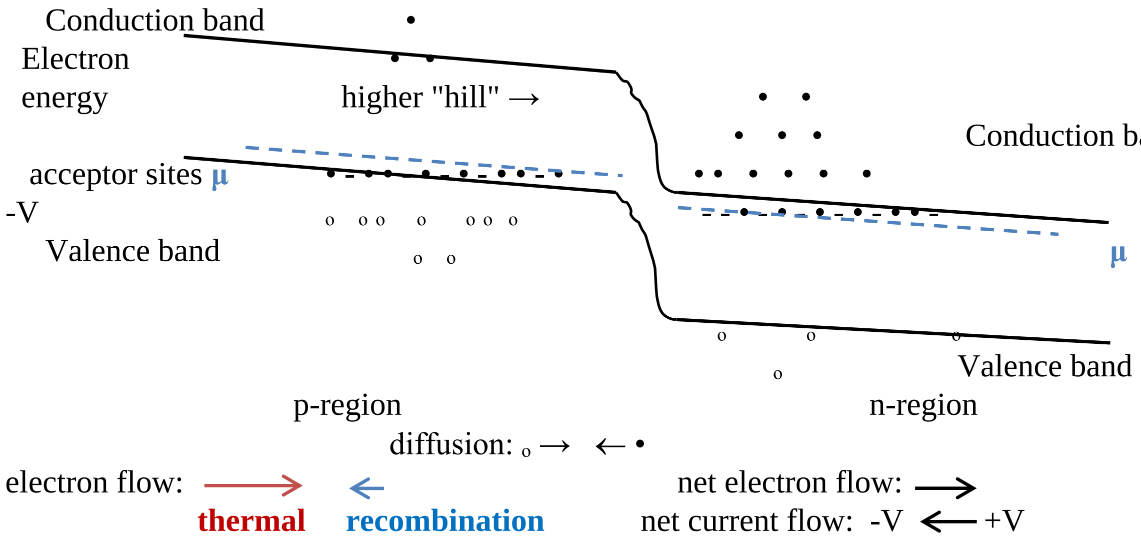
NOTE: The first peak region is due to the tunneling which happens very quickly - it is NOT diffusion limited as is the regular pn junction behavior.

## 2. Zener diodes

Zener diodes also use **tunneling**, but in the **reverse bias**. We again need a very small transition gap between the p-type and n-type materials.

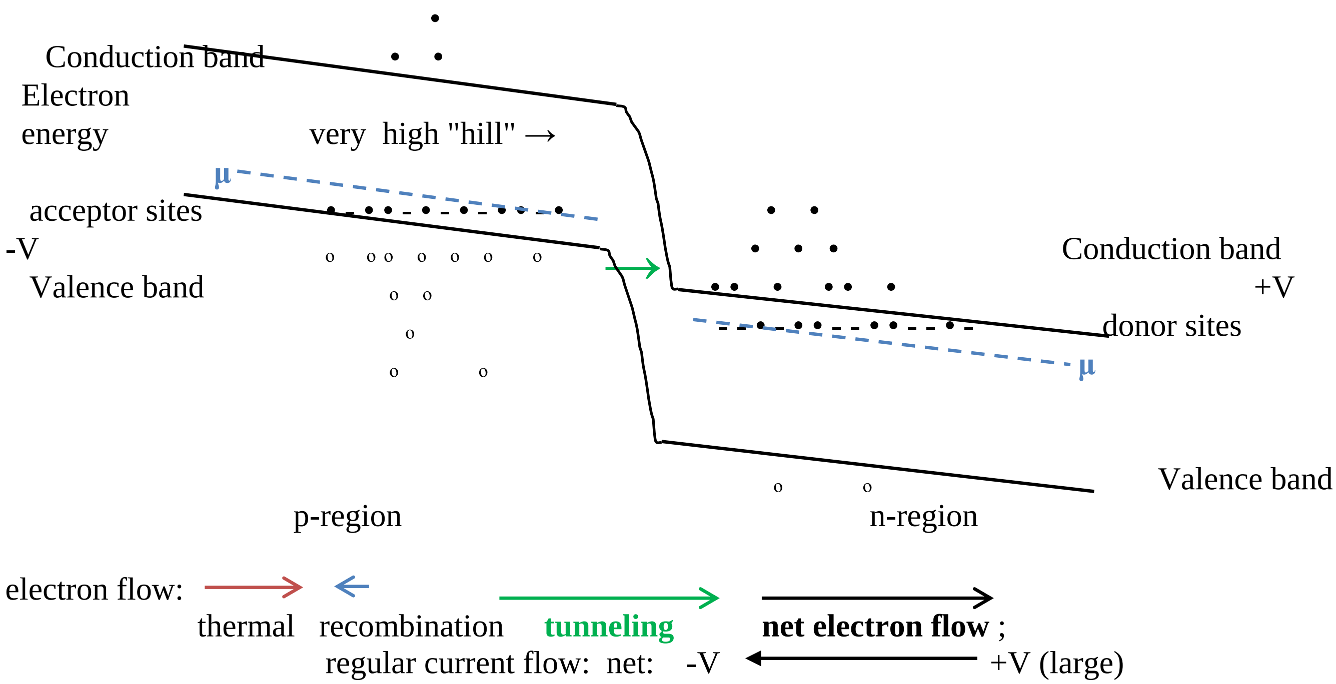
First review the normal reverse bias on a p-n junction: If we apply a negative voltage to the p-side (and hence a positive voltage to the n-side), we will again cause a shift in the energy diagram. Since electrons are negative charged particles, the electron energy will increase if we apply a negative voltage, and will decrease if we apply a positive voltage. Hence we get the following energy-space diagram:

**REVERSE BIASED JUNCTION**




Now let's increase the reverse bias so that **the essentially filled valence band in the p-type region is directly across from the relatively empty conduction band in the n-type**:

**VERY REVERSE BIASED JUNCTION** (zener breakdown region)




From the tunneling that occurs, the current going from the -V to the +V increases dramatically! To prevent damage, a current limiter is usually employed with zener diodes.

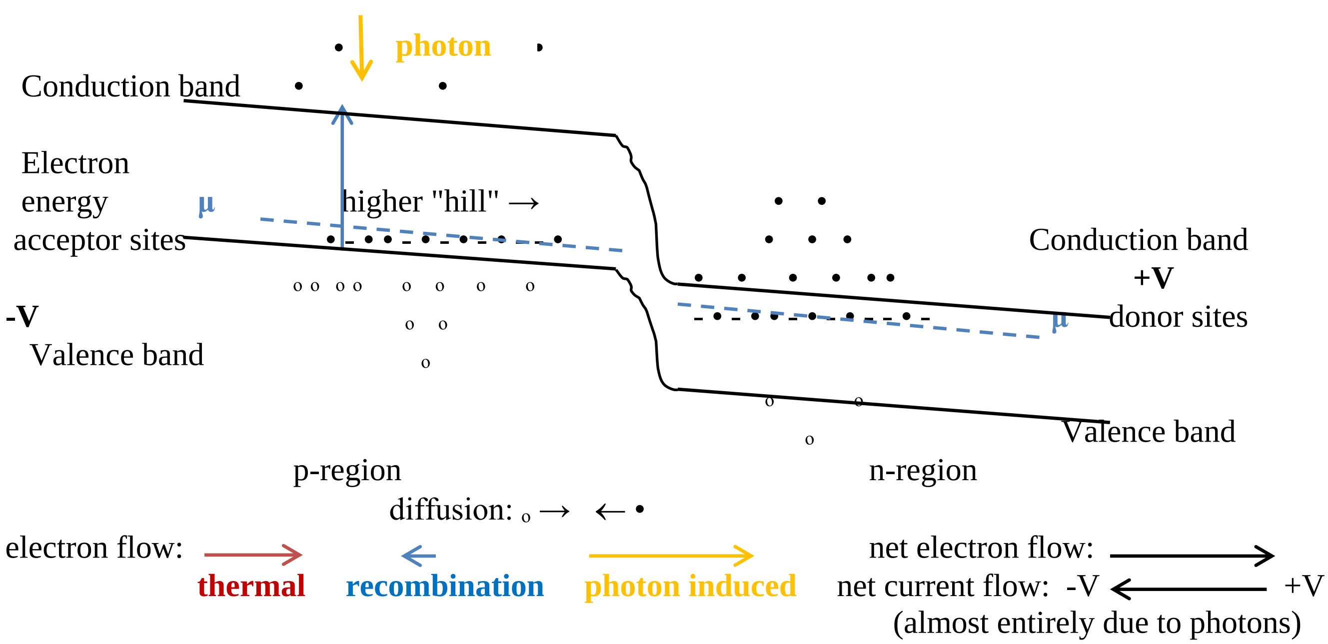
**Review**: Note that **tunneling occurs in the FORWARD BIAS for the tunneling diode**, and results in "negative" resistance for a small voltage range. **Tunneling also occurs in the Zener diode, but in the REVERSE BIAS**. Note that this Zener breakdown is quite different from the regular avalanche breakdown that destroys regular diodes.

## 3. Photo diodes

We can use the pn junction properties to relate light to current in the following way. First, operate a pn junction in **reverse bias** so that the recombination current is very low. Then **shine light on the p side** of the junction so that electrons in the valence band can absorb the photons and jump up to the conduction band. Then the electrons can simply fall down the "hill". The more photons there are, the more electrons that will jump up! Since the normal thermal current is very small, and the recombination current in reverse bias is even smaller, the current is almost entirely due to the electrons that jump up due to the photons. Only for very dim light will the small normal thermal current provide a background "noise". Also the amount of reverse bias voltage only affects the recombination current, but this current is very small. Therefore, **the amount of reverse bias voltage has very little effect**.

Note that the photons must be energetic enough to raise the electrons over the energy gap: $\mathbf{hf_{photons} \geq E_{gap}}$.
For silicon, $E_{gap} = 1.11\,\text{eV}$; thus $f_{min}h = E_{gap}$ leads to $f_{min} = 2.68 \times 10^{14}\,\text{Hz}$, and $\lambda f = c$ leads to $\lambda_{max} = 1.12 \times 10^{-6}\text{m}$ which is in the infrared. [Recall that the upper limit of red light is $\lambda_{red} = 700\,\text{nm}$, which leads to $f_{red} = 4.29 \times 10^{14}\,\text{Hz}$ and $E_{red} = 1.78\,\text{eV}$.]

**REVERSE BIASED JUNCTION**

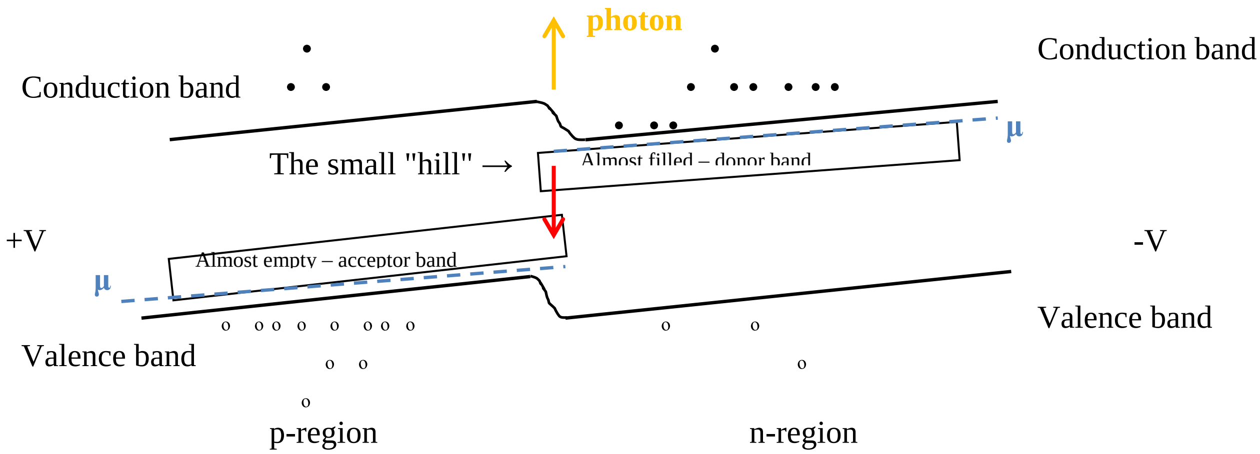



Note: a **solar cell** can be created by using an **unbiased pn diode**. We let the **light shine on the p side** which will cause extra electrons on the p side which will flow down the unbiased hill and set up a $\Delta V$ which can cause current and hence power.

## 4. LED's (light emitting diodes)

For a light emitting diode we need to **get light out** of (instead of absorbing light by) a pn junction. To do this, we need to have electrons drop down from the conduction band into holes in the valence band (rather than electrons jump up from the valence band to the conduction band as in photo diodes). To accomplish this we use a **heavily doped** p-type and a heavily doped n-type materials in a pn junction. If we **forward bias** this junction, then we can **get the conduction band full of electrons from the n-side over the valence band full of holes from the p-side**, as the following electron energy vs position diagram indicates:

**FORWARD BIASED JUNCTION** (heavily doped p and n sides)




Recall that the energy given off by the electrons in falling into the holes will be **photons of energy equal to the energy gap**. Thus for visible light emitting diodes, we must make sure that the energy gap is at least that at the red end of the visible spectrum (as calculated on the previous page): $E_{gap} > 1.78\text{ eV}$ . This will then provide a low power way of providing light (of one color). Also note that we need a **direct gap** semiconductor for an LED.

A **diode laser** is an LED (see above) with polished ends (see picture below) to get more stimulated emissions rather than the normal spontaneous emissions. **The high density of electrons in the n-type and the high density of holes in the p-type material are the source of our population inversion** that is necessary for the operation of a laser (more photons emitted than absorbed).