The Meaning of Fermi-Level And Related Concepts (Like Band-Bending)

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The Fermi level is a term derived from statistical mechanics and used to calculate the number of mobile carriers present in a solid. The Fermi Level is also an energy level. In a semiconductor, this level is located somewhere in the "forbidden"energy gap. It is "landmark"feature in the band-dege versus position diagram, frequently encountered in the electronics component literature. A view of this diagram is shown here.
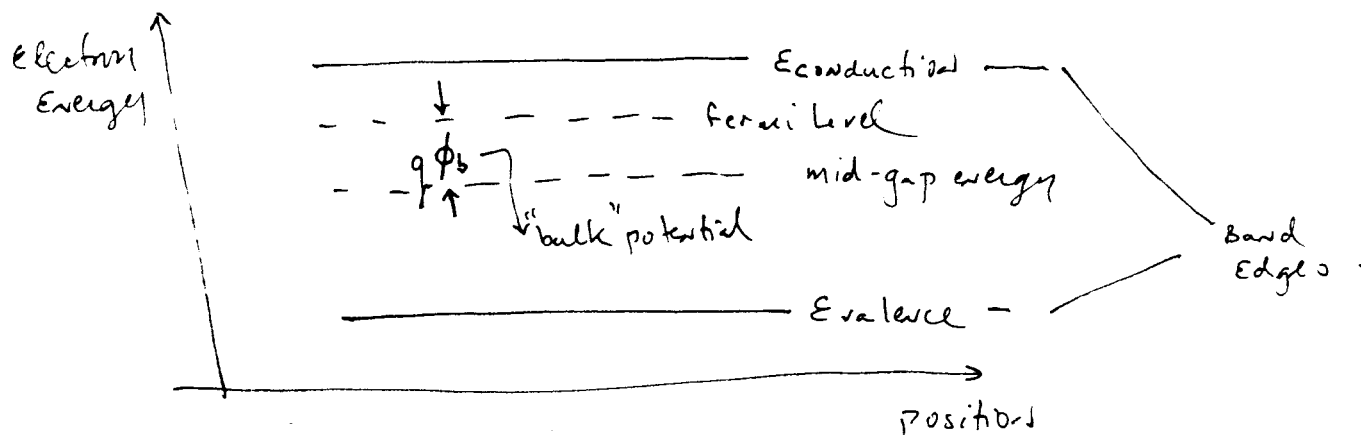

Figure 1: The band-edge versus position diagram

Energies are plotted against spatial position in a material. The major landmarks on this diagram (in addition to the Fermi Level itself) are the band edge energies. These are the energies of the conduction band minimum, $\mathcal{E}_{conduction}$, and the valence band maximum $\mathcal{E}_{valence}$. As the band edge

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extrema are zeros of kinetic energy, since $\frac{\partial \mathcal{E}}{\partial k}$ is zero at these extrema. This implies $\vec{v}$ is zero. Thus, the position of the band edge as a function of position changes with *potential* energy. And since the potential is the same for the conduction and valence bands, these band edge lines maintain constant separation through the diagram. The mid-gap energy is midway between conduction and valance band extrema.

Some notes are in order:

- The diagram expresses the energy of an *electron*. An electron would move right if the energy gradient is negative (while a positive charge would move left).

- Promoting an electron to a higher energy position on the diagram means work is done on the electron.

- As the band edges reflect changes in potential energy, they *bend* as the potential changes with position.

- Energy (Joules) is converted to electrostatic potential (voltes) by dividing energy by q, the charge on the electron.

In fig. 2, we see the results of running a constant electric field through the solid.
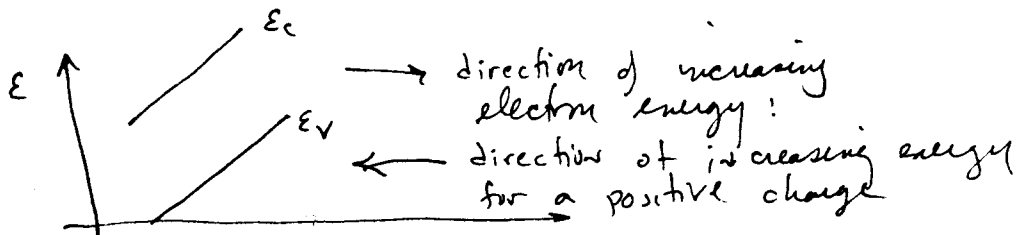

Figure 2: The effect of a constant electric field on the band-edge vs position diagram

The bands simply tip up, and maintain their straight-line shape. An electron moving under this field would move to the left. A hole would move right. Under the Franklin convention, the electric field is positive.

Thus, the band-dege versus position diagram helps us understand carrier motion; but it is no more useful than the potential vs position diagram. The addition of the Fermi Level landmark makes the presentation more powerful. This is because the position of the Fermi Level with respect to the band edges define the mobile charge occupancy of the bands:

> *The closer the Fermi Level is to the conduction band, the more mobile electrons are present in that band at the position referred to in the band edge versus position diagram. Similarly, the closer the Fermi Level is to the valence band, the more mobile holes are present in this band.*
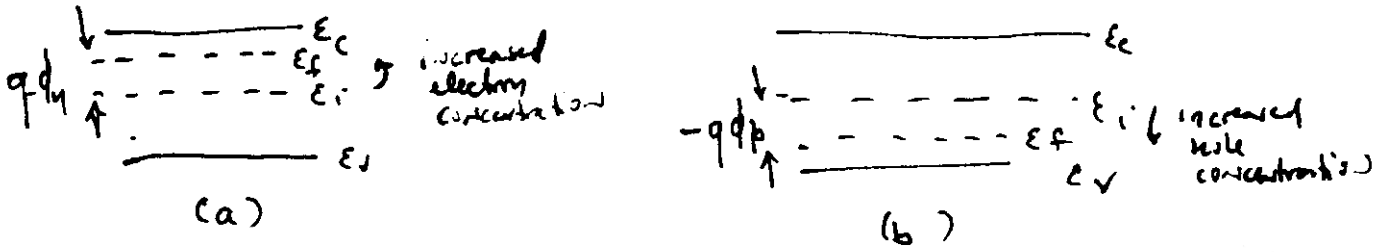
This is seen in the figrures below.

Figure 3: band-edge vs position diagrams for n- and p-type material

n-Type	p-Type
$n \equiv$ mobile electron density	$p \equiv$ mobile hole density
$n_p \equiv$ mobile electrons in p-material	$p_n \equiv$ mobile holes in n-material
$n_n \equiv$ majority electron density	$p_p \equiv$ majority hole density
$\phi_n \equiv$ "bulk" potential for n-type	$\phi_p \equiv$ "bulk" potential for p-type
$n_n = n_i \exp\left(\frac{q\phi_{bn}}{kT}\right)$	$p_p = n_i \exp\left(\frac{-q\phi_{bn}}{kT}\right)$
$n_p = n_i \exp\left(\frac{-q\phi_{bn}}{kT}\right)$	$n_p = n_i \exp\left(\frac{q\phi_{bn}}{kT}\right)$
$\phi_{bn} = \frac{kT}{q} \ln\left(\frac{N_d}{n_i}\right)$	$\phi_{bp} = \frac{kT}{q} \ln\left(\frac{N_a}{n_i}\right)$

When no fields are present, the Fermi level represents a diffusion (or chemical) potential for the carrier with which it is associated. Gradients in diffusion potential indicate the particles tendency to move (i.e., diffusion

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currents are proportional to the gradient of diffusion potential). When the
semiconductor background concentration changes from p- to n-type, there is
a net diffusion potential differennce of $(\phi_n - \phi_p)$. This potential difference
is "bucked out "by a true electrostatic drop. This electrostatic drop gives
rise to an electric field which prevents further migration of charge. This is
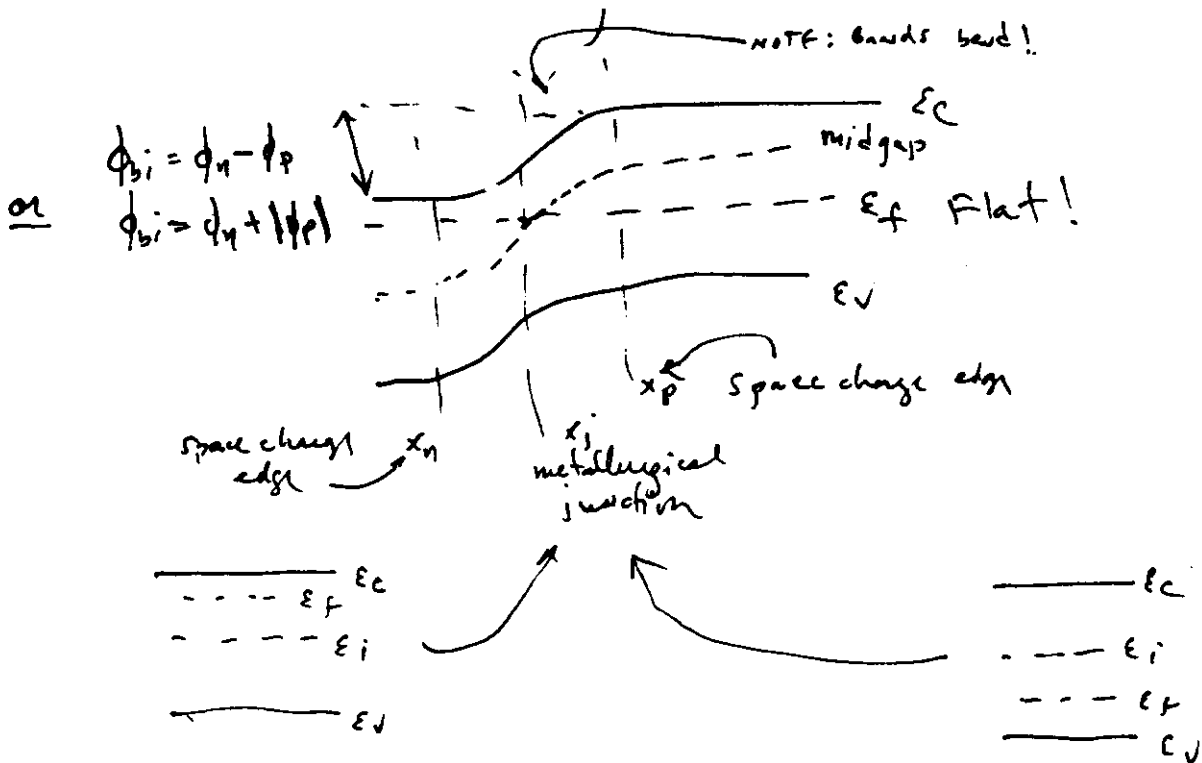all shown in the following figures.

Figure 4: band-edge vs position diagrams for a pp-junction illustrating the
"bucking out"of diffusion by electrostatic potential

We see that the Fermi-level has a number of functions. First, it defines
the mobile carrier occupancy of the bands. In addition, its gradient is propor-
tional to the *total* current (this includes both drift and diffusion components
of transport. Finally, it determines the likelihood of occupancy of a given
state. these states can be present in the band or (as a result of defects) in
the band gap.

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NOTE: from above equation set:

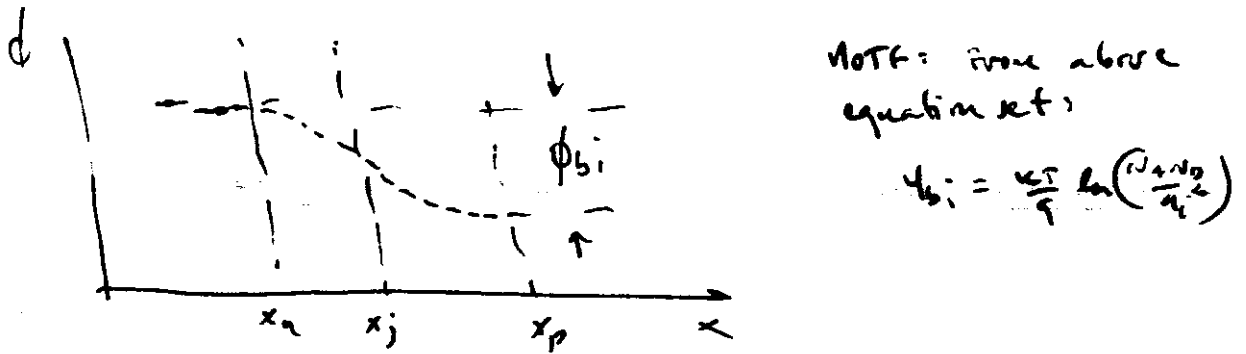$$\phi_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Figure 5: Plot of Franklin-convention electrostatic potential as a function of position for the junction shown in fig.4

To illustrate this, consider a donor trap whose ground-state energy is in the semiconductor band gap. If the Fermi level is well above this energy, the donor will, most likely, be occupied by an electron (neutral). On the other hand, if the Fermi level is well below this trap energy, the electron will be absent and the trap will be positively charged. For acceptor traps, the opposite is true (kind of). If the Fermi level is above the trap, it will most likely be occupied by an electron (negatively charged). If it is below the Fermi level, it will neutral. This is illustrated in the figure below.
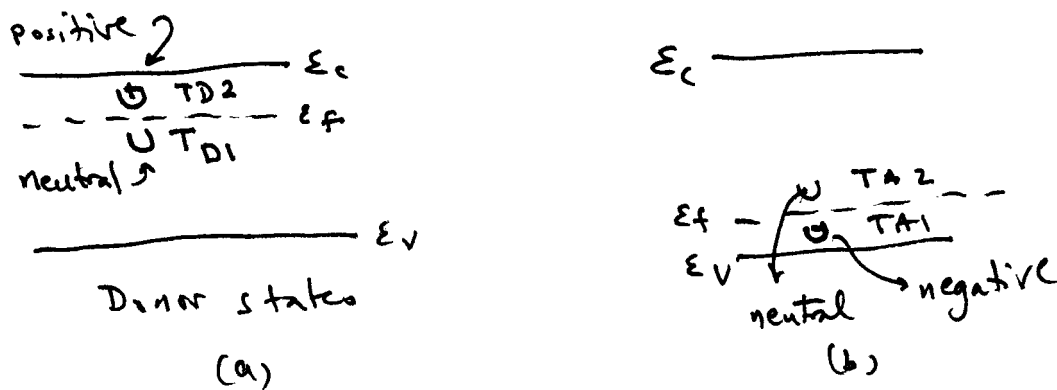

Figure 6: Influence of the position of the Fermi level on trap occupancy.