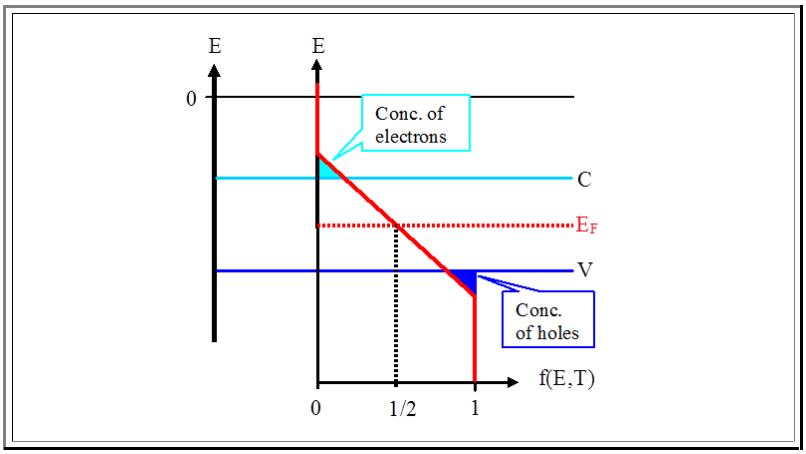
2.2 Basic Semiconductor Physics

2.2.1 Intrinsic Properties in Equilibrium

- In this subchapter we deal with basic semiconductor properties and simple devices like **p-n** junctions on a somewhat simplified, but easy to understand base. It shall serve to give a good basic understanding, if not "gut feeling" to what happens in semiconductors, leaving more involved formal theory for later.
  - However: Intrinsic semiconductors are theoretical concepts, requiring an absolutely perfect infinite crystal. Finite crystals with some imperfections may have properties that are widely different from their intrinsic properties.
  - As a general rule of thumb: If you cannot come up with a material that is at least remotely similar to what it should be in its "intrinsic" state, it is mostly useless because then you cannot manipulate its properties by doping.
  - That is the major reason, why we utilize so few semiconductors – essentially **Si**, **GaAs**, **GaP**, **InP**, **GaN**, **SiC** and their relatives – and tend to forget that there is a large number of "intrinsically" semiconducting materials out there. For a short list activate the (German) link.
- Silicon crystals are pretty good and thus are closest to truly intrinsic properties. But even with the best **Si**, we are not really close to intrinsic properties, see exercise **3.1-1** for that. Nevertheless: *This chapter always refers to silicon, if not otherwise stated!*
  - A few very basic aspects about semiconductors, including some specific expressions and graphical representations, will be taken for granted; in case of doubt refer to the link with an **alphabetical list of basic semiconductor terms**.

Fermi Energy and Carrier Density

- In this first section we review the properties of **intrinsic semiconductors** . We make two simplifying assumptions at the beginning (explaining later in more detail what they imply):
  - The semiconductor is "**perfect** ", i.e. it contains no crystal defects whatsoever.
  - The effective density of states in the conduction and valence band, the mass, mobility, lifetime, and so on of electrons and holes are identical. (See below for any detail about these quantities.)
- All we need to know for a start then is the magnitude of the band gap E_g. The Fermi energy then is exactly in the middle of the forbidden band; we can deduce that as follows:
  - Namey, by just looking at a drawing schematically showing the density of electrons in the valence and conduction band where, for ease of drawing, the Fermi distribution is shown with straight lines instead of the actual curved shape.



  - Note that in the standard literature (especially in the English language scientific literature), typically one doesn't sharply distinguish between *carrier density* and *carrier concentration*. If in doubt, look for the unit of measurement relevant in the given equation.
- The density of electrons, n_e, in the conduction band is given exactly by

$$n_e = \int_{E_C}^{E'} D(E) \cdot f(E,T) \cdot dE$$

  - With E' = energy of the upper band edge.

- With the usual approximations:
  - Boltzmann distribution instead of Fermi distribution.
  - Substitution of an **effective density of states**, N_{eff} at the band edge instead of the true, energy-dependent density.
  - Integration from the lower band edge E_C to infinity

  we obtain

$$n_e = N_{eff}^{\ e} \cdot \exp\left(-\frac{E_C - E_F}{kT}\right)$$

- The light blue triangle in the picture symbolizes this density!

N_{eff}^{e} (with the factor two for spin up/spin down included) can be estimated from the free electron gas model in a fair approximation to

$$N_{eff}^{e} = 2\left(\frac{2\,\pi m kT}{h^2}\right)^{3/2}$$

- How this is done and how some numbers can be generated from this formula (look at the dimensions in the formula above and start wondering) can be found in the link.

In an intrinsic semiconductor in thermal equilibrium, all electrons in the conduction band come from the valence band. The density of holes in the valence band, n_h , thus must be exactly equal to the density of electrons in the conduction band, or

$$n_e = n_h = n_i = \text{intrinsic density}$$

- The dark blue triangle in the picture then symbolizes the hole density.
- **Important:** This is how holes are *defined* , and for good reasons; as we will see (rather soon), **only** the empty *valence band* states can reasonably be considered as being occupied by holes (= *mobile* positive charge carriers).
- Given the assumptions made above and the symmetry of the Fermi distribution, the unavoidable conclusion is that the Fermi energy is exactly in the middle of the band gap.

Carrier Density and Conductivity

The carrier densities are decisive for the conductivity (or resistivity) of the material. If you are not familiar (or forgot) about conductivity, mobility, resistivity, and so on and how they connect to the average properties of an electron gas in thermal equilibrium, go through the following basic modules:

- Ohm's Law and Materials Properties
- Ohm's Law and Classical Physics

We thus have the density of mobile carriers in both bands and from that we can calculate the **conductivity** σ via the standard formula

$$\sigma = e \cdot (\mu_e \cdot n_e + \mu_h \cdot n_h)$$

- provided we know the **mobilities** μ of the electrons and holes, μ_e and μ_h, respectively.

Again, simplifying as much as sensibly possible, with $\mu_e = \mu_h = \mu$ we obtain

$$\sigma = 2e\mu \cdot N_{eff}^{\ e} \cdot \exp\left(-\frac{E_C - E_F}{kT}\right) = 2e\mu \cdot N_{eff}^{e} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

- because we have $E_C - E_F = E_g/2$ (with the fundamental band gap energy E_g) for the intrinsic case as discussed so far.

- This gives us already a good idea about the comparable magnitudes and especially the temperature dependences of semiconductors, because the exponential term overrides the pre-exponential factor which, moreover, we may expect not to be too different for *perfect intrinsic* semiconductors of various kinds.