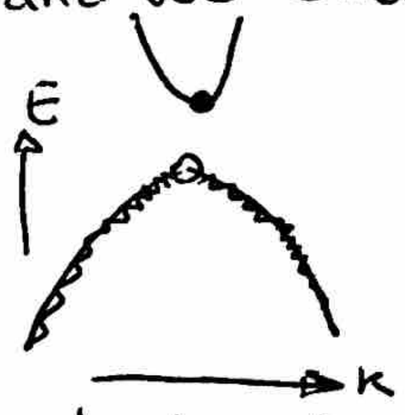
Semiconductor Physics

Suppose we start with an insulator or semiconductor and we excite one electron from valence band to the conduction band.



This excitation may be due to absorbing a photon, or it might be a thermal excitation. The absence of an electron in the valence band is known as a hole. Since a completely filled band is inert, it is very convenient to only keep track of the few holes in the valence band. the $\bar{e}$ can fall back into the empty state that is the hole, emitting energy (a photon say) and "annihilating" both the $\bar{e}$ from the conduction band and the hole from the valence band.

Effective mass of e^-

Assume that near the bottom of the conduction band $k = k_{min}$ the energy is given by $E = E_{min} + \alpha|k - k_{min}|^2 + \dots$ with $\alpha > 0$ where dots mean higher-order terms in the deviation from k_{min}. Then we define the effective mass to be: $\frac{\hbar^2}{m^*} = \frac{\partial^2 E}{\partial k^2} = 2\alpha$ at the bottom of the band.

Correspondingly, the group velocity is given by $v = \frac{\nabla_k E}{\hbar} = \frac{\hbar(k - k_{min})}{m^*}$

Free $\bar{e}$: $E = \hbar^2|k|^2/2m$ $\quad v = \frac{\nabla_k E}{\hbar} = \frac{\hbar k}{m}$

Effective mass of h^+

We can also define an effective mass for holes in a similar way (a bit more complicated). For the top of the valence band, the energy dispersion for $\bar{e}$ would be $E = E_{max} - \alpha|k - k_{max}|^2 + \dots$ with $\alpha > 0$.

The modern convention is to define the effective mass for holes at

Drude transport:

$$m_e^* \frac{dv}{dt} = -e\underbrace{(\vec{E} + v \times \vec{B})}_{\text{Lorentz Force}} - \underbrace{m_e v/\tau}_{\text{drag force with scattering time } \tau}$$

determines μ mobility

main failure: It doesn't treat the Pauli exclusion principle properly
e.g. in metals the high density of $\bar{e}$ makes the Fermi energy extremely high

but in semiconductor or band insulators, when only a few $\bar{e}$ are in the conduction band then we can consider this to be a low density situation and to a very good approximation we can ignore Fermi statistics.

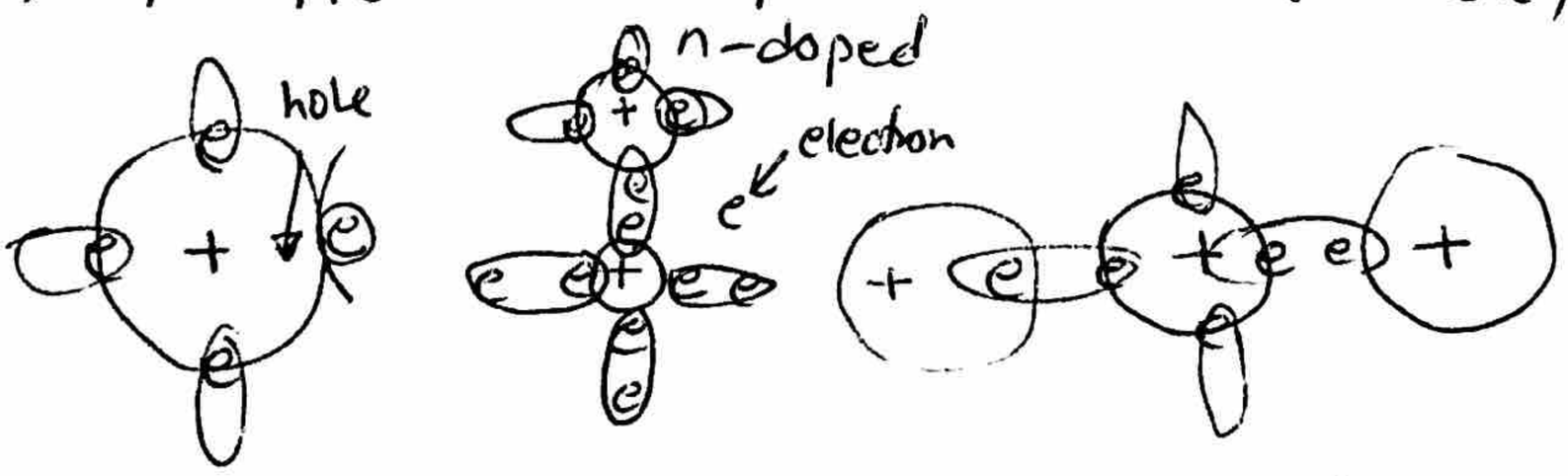
* $\bar{e}$ mobility is generally defined as the ratio of the velocity to the electric field $\mu = |v|/|E| = e\tau/m^*$

For holes: $m_h^* dv/dt = e(E + v \times B) - m_h^* v/\tau$

Doping Electrons or holes with impurities

- In pure band insulator or semiconductor, if we excite $\bar{e}$ from the valence to conduction band $n = p$: intrinsic

P-doped Al P Si (Intrinsic)



- Once we add a single n-dopant to an otherwise intrinsic sample of Si, we get a single electron above the gap in the conduction band. This $\bar{e}$ behaves like a free particle with mass m_e^*. However in addition we have a single extra positive charge $+e$ at some point in the crystal due to P nucleus. the free $\bar{e}$ is attracted back to this positive charge

and forms a bound state that is similar to hyrogen atom.

Difference to atomic hydrogen: * effective mass m_e^*

* instead of two charges attaching each other with $V = \frac{e^2}{4\pi\epsilon_0 r}$ they attract each other with $V = \frac{e^2}{4\pi\epsilon\epsilon_0 r}$ where ϵ_r is relative permittivity of the material.

Energy eigenstates of the hydrogen atom $E_n^{H\text{-atom}} = -\frac{R_y}{n^2}$; $R_y = \frac{me^2}{8\epsilon_0^2 h^2} \approx 13.6^{eV}$

Radius of hydrogen atom $r_n \approx n^2 a_0$ with Bohr radius $a_0 = \frac{4\pi\epsilon_0 \hbar^2}{me^2} \sim 0.5\text{Å}$

$\Rightarrow$ hydrogenic impurity state gives precisely the same expression only

ϵ_0 is replaced by $\epsilon_0\epsilon_r$ and m is placed by m_e^*. $R_y^{eff} = R_y\left(\frac{m_e^*}{m}\frac{1}{\epsilon_r^2}\right)$

$a_0^{eff} = a_0\left(\epsilon_r \frac{m}{m_e^*}\right)$

Dielectric of semiconductors are typically high ~ 10 } $R_y^{eff} \ll R_y$

Effective mass is typically small } $a^{eff} \gg a_0$

In ^{18}Si the effective Rydberg $R_y^{eff} \sim 0.1eV$ $a_0^{eff} \sim 30\text{Å}$

This donor impurity forms an energy eigenstate with energy just below the bottom of the conduction band. At zero temperature this eigen state will be filled, but it takes only a small temperature to excite a bound e^- out of a hydrogenic orbital and into the conduction band.