Do same thing for holes in valence band

$$f_h(E) = 1 - f(E)$$
$$= 1 - \frac{1}{e^{(E-\mu)/kT}+1} = \frac{e^{(E-\mu)/kT}}{e^{(E-\mu)/kT}+1}$$

$$\frac{e^x}{e^x+1} \cdot \frac{e^{-x}}{e^{-x}} = \frac{1}{1+e^{-x}}$$

$\leftarrow \mu$

$\leftarrow \epsilon$

$\mu - \epsilon$ = positive

(E = energy of electrons, pull in not energy of holes which would have opposite sign)

$$= \frac{1}{e^{(\mu-E)/kT}+1}$$
$$\simeq e^{-(\mu-E)/kT}$$

Same integral

Typo pg 206

$$p = \int_{-\infty}^{E_v} \frac{D_h(E)}{V}\, f_h(E)\, dE$$

mod for holes

pg 206
Eqn 8.42
Typos in Kittel!

$$p = \underbrace{2\left(\frac{m_h^* kT}{2\pi\hbar^2}\right)^{3/2}} e^{-(\mu-E_v)/kT} \quad \text{(same as Kittel)}$$

↳ could be called p_0, but isn't in Kittel. I'll use that symbol later, though

Multiply together

$$np = 4\left(\frac{kT}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2} e^{-\frac{1}{kT}(E_c - \cancel{\mu} + \cancel{\mu} - E_v)}$$

$$\boxed{np = \underbrace{4\left(\frac{kT}{2\pi\hbar^2}\right)^3 (m_e m_h)^{3/2}}_{n_0 p_0} e^{-E_G/kT}}$$

only assumption: μ far from both CB + VB

could be "intrinsic", could be "doped"

↳ but carefully ... 1st condition is still met "compensated" "intrinsic": $n \simeq p$ since all promoted electrons leave holes behind

no added impurities

pg 207
Eqn 8.45

$n^2 = \ldots$

$$\boxed{n = 2\left(\frac{kT}{2\pi\hbar^2}\right)^{3/2}(m_e m_h)^{3/4}\, e^{-E_g/2kT}}$$

"n_i" ← intrinsic

Also have when $n = p$,

$$\cancel{2}\left(\frac{m_e kT}{\cancel{2\pi\hbar^2}}\right)^{3/2} e^{-(E_c-\mu)/kT} = \cancel{2}\left(\frac{m_h kT}{\cancel{2\pi\hbar^2}}\right)^{3/2} e^{-(\mu-E_V)/kT}$$

$$e^{2\mu/kT} = \left(\frac{m_h}{m_e}\right)^{3/2} e^{(E_c+E_V)/kT}$$

define $E_V = 0$
then $E_c = E_g$
or $E_{mid} = \frac{E_c+E_V}{2}$

$$\mu = \frac{kT}{2}\ln\left[\ \ldots\ \right]$$

$$= \frac{kT}{2}\left[\frac{3}{2}\ln\left(\frac{m_h}{m_e}\right) + \frac{E_g}{kT}\right]$$

$$\boxed{\mu = \underbrace{\tfrac{1}{2}E_g}_{E_{mid}} + \frac{3}{4}kT\ln\frac{m_h}{m_e}}$$

pg 207
Eqn 8.47

for intrinsic only

← small

μ close to mid gap for intrinsic

Side Note: next page in [illegible] discusses "mobility" [illegible] which is $\frac{\text{conductivity}}{n \cdot e}$

"If you have charges, how easily do they move?"

also $\frac{N}{T}$

Horrible: mobility also given symbol μ

μ_e = electron mobility

μ_h = hole mobility

Subscripts necessary to mean that the symbol μ now has completely unrelated meaning!

Recall $\sigma = \frac{ne^2\tau}{m}$ → $\mu_e = \frac{ne^2\tau/m}{ne} = \frac{e\tau}{m}$

↑ in semiconds, cond. dominated by temp. dependence of n! (τ weaker dependence on temp.)

day 3 pg 3

Doping

Ex.

"Donor"

"n-type"

Si

P ← 4 electrons to covalent bonds + 1 extra electron (and one proton)

Si Si Si

Differences

1) extra electron moves around silicon w/ effective mass m^*

2) positive charge screened by core electrons
→ dielectric constant, as usual with materials.
ϵ_r ↳ this is called relative [illegible] value of ϵ.

(+ion) P e^- extra electron

Table of ϵ in pg [illegible] Table 4

Attraction just like ⊕ ⊖ hydrogen

hydrogen | Donor

ionization (binding) energy

$$E = \frac{e^4 m}{2(4\pi\epsilon_0)^2\hbar^2} \longrightarrow$$

$$= 13.6\text{ eV} \qquad = \boxed{\frac{13.6\text{ eV}}{\epsilon_r^2}\left(\frac{m^*}{m}\right)}$$

Bohr radius $a_0 = \frac{4\pi\epsilon_0\hbar^2}{me^2} \qquad = \boxed{.53\text{ Å}\ \frac{\epsilon_r}{m^*/m}}$

$= .53\text{ Å}$

P donor in Si: $m^* = .2m$, $\epsilon = 11.7$

↓

$\boxed{a_0 = 30\text{ Å}}$ 30–50 Å

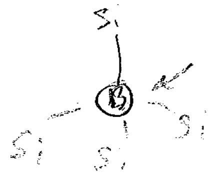
$E_d = \boxed{20\text{ meV}}$ 10–80 meV ← ground state = 20 meV [illegible]

≈ 30 [illegible] meV

[illegible] ground state E_d = 30 meV
[illegible] ≈ 30–120 meV

"Acceptor"

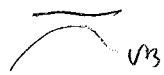
$(s^1p^1p^1p^1)$



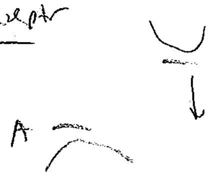
4 electrons to covalent bond + 1 Extra hole (and neg. charged nucleus)

hole binding to neg. nucleus → same ionization energy + Bohr radius (except hole m^*, not electron m^*)

acceptor binding E



<u>Donor + Acceptor</u>



electrons drop down to A level

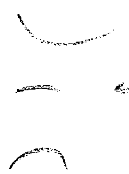
if $N_D > N_A$ n-type

$N_A < N_D$ p-type

"compensated" → roughly equal, or at least, lots of both types

<u>Amphoteric</u> - ex. Si in GaAs, could be either

<u>Nonhydrogenic</u>



← states deep in band

tend to happen when big lattice distortion

because dopant not very like host

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day 35 pg 1

<u>Background</u> - unintentional $\approx 10^{14}\ cm^{-3}$ ($\approx$ 1 part in 10^9) for best samples

intentional: often $\approx 10^{17}$ - $10^{18}\ cm^{-3}$

(my own samples $3\cdot10^{14}$ - $3\cdot10^{15}\ cm^{-3}$)