EEE 6212
Semiconductor Materials

Lecture 10: Doping

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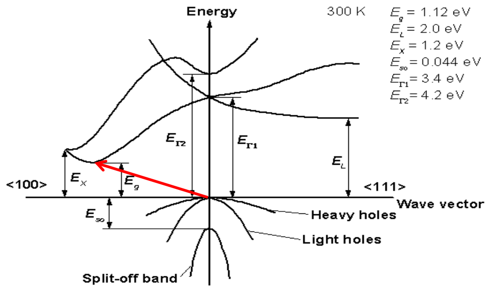
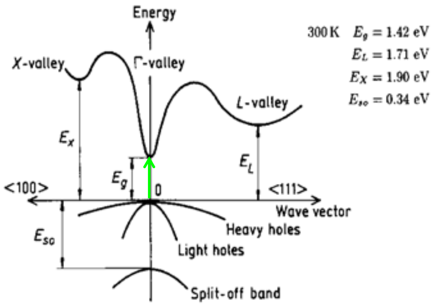
- review of band structures
- conductivity
- general formulae for charge carrier densities, DOS and Fermi distribution
- intrinsic semiconductors
- doping as electrically active, substitutional point defects in the lattice
- donators and acceptors; flat vs. deep levels
- intrinsic, saturation and extrinsic range

typical semiconductor band structures

review of band structures at room temperature





Si GaAs

http://www.ioffe.ru/SVA/NSM/Semicond

conductivity, part 1: the basics

general equation for conductivity:

$$\sigma = e\,(n\mu_n + p\mu_p)$$

where e=1.6022×10^{-19} C is the elementary charge,

n is the (free) electron density and

p is the hole density,

μ is the mobility of charge carriers (electrons/holes)

Note that Ohm's law states $\underline{\sigma}\,\underline{\mathbf{E}}=\underline{\mathbf{j}} = -en\underline{\mathbf{v}}_e + ep\underline{\mathbf{v}}_p$ where $\underline{\mathbf{v}}_d$ denotes the drift velocity of the charge carrier type, given by $\underline{\mathbf{v}}_e=-\mu_e\underline{\mathbf{E}}$ and $\underline{\mathbf{v}}_p=\mu_p\underline{\mathbf{E}}$.

charge carrier density, DOS & Fermi distribution

charge carrier densities:

1. electron density: $n=\int_{E_c}^{\infty} D_c(E)\, f(E,T)\, dE$

2. hole density: $p=\int_{-\infty}^{E_v} D_v(E)\, [1-f(E,T)]\, dE$

where $D_{c,v}$ are the density of states (DOS) in the conduction and valence band and are approximately given by

$D_c(E) \approx 4\pi/h^3\ (2m_{e^*})^{3/2}\ \sqrt{(E-E_c)}$ (for $E>E_c$)

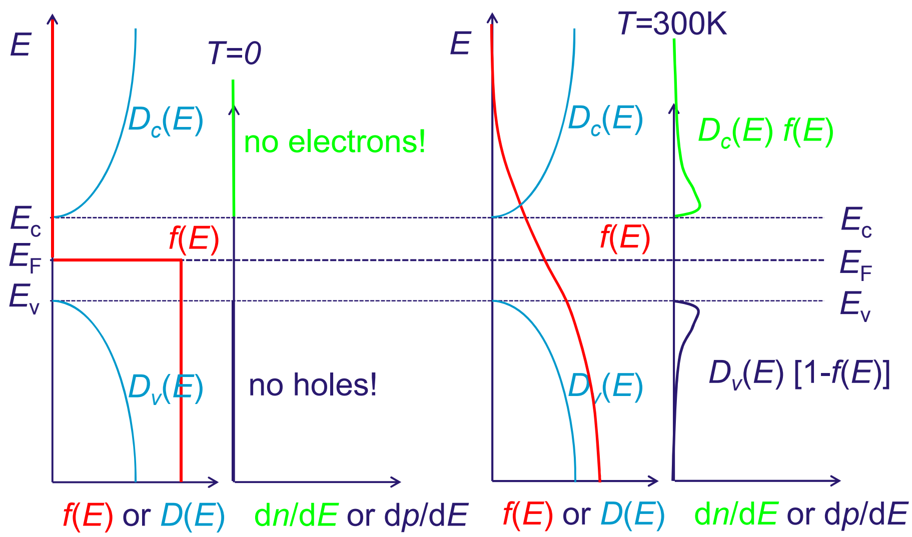
$D_v(E) \approx 4\pi/h^3\ (2m_{p^*})^{3/2}\ \sqrt{(E_c-E)}$ (for $E<E_v$)

$D=0$ for $E_v<E<E_c$ (forbidden: band-gap)

and $f(E,T)=1/\,[1+\exp\,(E-E_F)/(k_B T)] \approx \exp\,[-(E-E_F)/(k_B T)]$

is Fermi-Dirac distribution function for electrons at $E-E_F>>2k_BT$

charge carrier density, DOS & Fermi distribution



charge carrier density, DOS & Fermi distribution

insertion of Fermi-Dirac approximation yields:

1. electron density: $n \approx \underbrace{2\,(2\pi m_{e^*}\,k_B T/h^2)^{3/2}}_{N_c^*}\ \exp\,[-(E_c\text{-}E_F)/(k_B T)]$

2. hole density: $p \approx \underbrace{2\,(2\pi m_{h^*}\,k_B T/h^2)^{3/2}}_{N_v^*}\ \exp\,[(E_v\text{-}E_F)/(k_B T)]$

note: $n \cdot p = \underbrace{4\,(2\pi k_B T/h^2)^3\,(m_{e^*}\,m_{h^*})^{3/2}}\ \exp\,[-\underbrace{(E_c\text{-}E_v)}/(k_B T)]$

$= \quad N_c^* N_v^* \quad \exp\,[-E_g/(k_B T)]$

intrinsic semiconductors

for intrinsic semiconductors: electron density= hole density, i.e.

$n=p=n_i = 2\,(2\pi k_B T/h^2)^{3/2}\,(m_{e^*}\,m_{h^*})^{3/4}\ \exp\,[-E_g/(2k_B T)]$

insert numbers for Si at room temperature (300K):
E_g=1.12eV, $m_e \approx m_h \approx m_e$=9.1095×$10^{-31}$kg

$n \approx 1\times10^{16}$ m^{-3}= 1×10^{10} cm^{-3}

Compare to atomic density of Si:

8 atoms per unit cell with a=0.5431nm:

$n_{atoms}=8/a^3 \approx 5\times10^{28}$ m^{-3} =5×10^{22} cm^{-3}

This means there is only 1 electron for 5×10^{12} Si atoms!

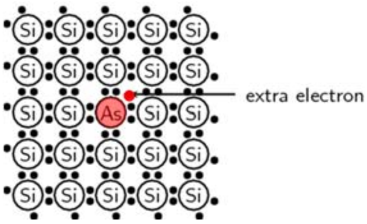
So, doping at the ppm level can change this dramatically!

doping: electrically active point defects

foreign atoms (impurities or intentionally implanted ions) act as dopants if they are

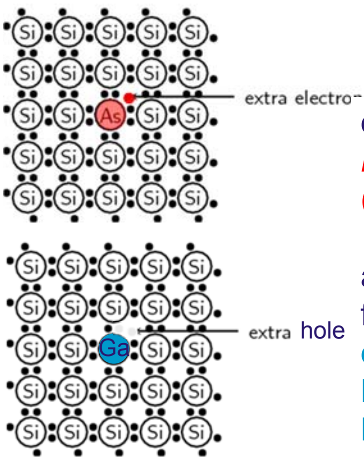
a) integrated ***substitutionally*** into the host lattice on lattice sites so that they

b) provide either an electron or a hole (i.e., they are ***electrically active***)



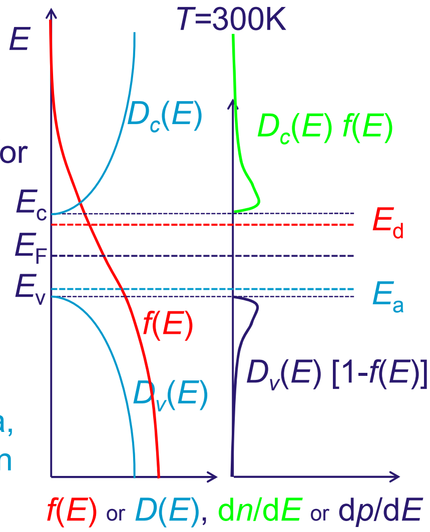
an As atom has 5 valence electrons and needs only 4 for bonding in the diamond lattice, so there is 1 free electron, which increases *n* dramatically

donators vs. acceptors; flat vs. deep levels



donators for *n*-doping: (N), P, As,

acceptors for *p*-doping: B, (Al), Ga, Be, Mg, Zn



intrinsic, for high, | saturation and extrinsic range medium, | low temperatures

intrinsic	saturation	extrinsic
no intentional doping	all dopants have given away their charges	donor electrons (e^-) or accepter holes (p^+) partially active
$n=p=n_i$	$n=N_d$ (or $p=N_a$)	$n=\sqrt{\tfrac{1}{2}N_c^* N_d}\exp[-(E_c-E_d)/(2k_BT)]$ with $N_d=N_d^+ + N_d^0$
$\sigma_i=en_i(\mu_e+\mu_p)$	$\sigma=eN_d\mu_e$ (or $\sigma=eN_a\mu_p$)	$\sigma\propto\exp[-(E_c-E_d)/(2k_BT)]$

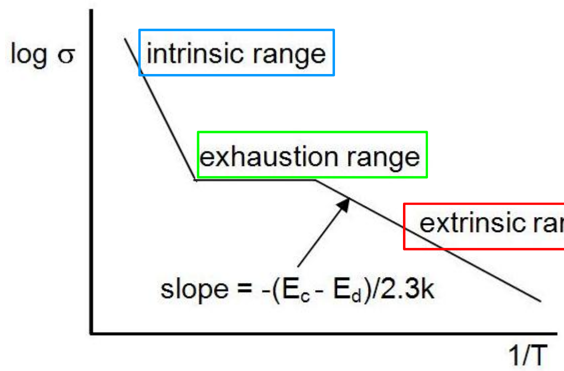
$n_i=\sqrt{N_c^* N_v^*}\exp[-E_g/(2k_BT)]$

$E_{F,i}=\tfrac{1}{2}(E_c+E_v)+\tfrac{3}{4}k_BT\ln(m_h^*/m_e^*)$

$E_F=\tfrac{1}{2}(E_c+E_v)+\tfrac{3}{4}k_BT\ln(m_h^*/m_e^*)+k_BT\,\mathrm{arsinh}[N_d/(2n_i)]$

$E_F=\tfrac{1}{2}(E_c+E_d)-\tfrac{1}{2}k_BT\ln(2N_c/N_d)$

conductivity, part 2: summary for n-doping



for p-doping: (E_a-E_v) instead of (E_c-E_d)