EEE 6212
Semiconductor Materials

Lecture 17: carrier lifetime and recombination

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- carrier lifetime in classical mobility model
- Debye length
- Fermi's golden rule
- radiative vs. Auger transitions
- carrier lifetime model in semiconductors:
  - A) non-radiative contributions by defects
  - B) radiative recombination
  - C) Auger recombination

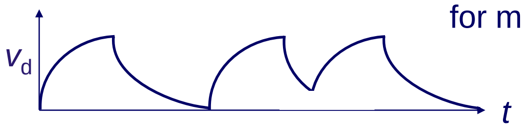
classical model of a charge carrier in an electric field

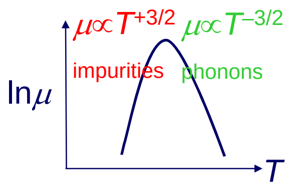
consider differential equation for drift velocity $\underline{\mathbf{v}}_d$ of an electron of mass m and charge $-e$ in an electric field $\underline{\mathbf{E}}$ with 'friction' b:

$m\, \partial v_d/\partial t + b v_d = F = -eE$

-> $v_d + \tau\, \partial v_d/\partial t = -eE\tau/m$ with relaxation time $\tau = m/b$

-> $v_d = v_{d,\infty}\,[1 - \exp(-t/\tau)]$ with $v_{d,\infty} = -eE\tau/m = -\mu E$ for mobility μ





-> mobility: $\mu = |\underline{\mathbf{v}}_{d,\infty}| / |\underline{\mathbf{E}}|$
or
lifetime of individual electron in CB: $\tau = \mu\, m/e$ $= 10^{-14}$-10^{-13}s

alternative model

consider time during which a discontinuity in space charge is dissipated by electrical conductance, e.g. injection of Δn electrons (of charge density $\rho = -e\,\Delta n$):

$$\left.\begin{array}{l} \mathrm{div}\ \underline{\mathbf{D}} = \rho = -e\,\Delta n \\ \underline{\mathbf{D}} = \varepsilon_0\varepsilon_r\,\underline{\mathbf{E}} \\ \underline{\mathbf{j}} = \sigma\,\underline{\mathbf{E}} \\ div\ \underline{\mathbf{j}} = -\partial\rho/\partial t \end{array}\right\} \quad \partial\rho/\partial t = -\sigma/(\varepsilon_0\varepsilon_r)\,\rho \ \ \text{->}\ \ \rho \propto \exp(-t/\tau)$$

with $\tau = \varepsilon_0\varepsilon_r/\sigma$

Debye length

consider current density through electrodes into semiconductor when electrical current $\underline{\boldsymbol{j}}$ due to div$\underline{\mathbf{E}}=\rho/(\varepsilon_0\varepsilon_r)$ compensates the diffusion current due to the concentration gradient

$\sigma\underline{\mathbf{E}} + eD_n$ grad $\Delta n = 0$ with $D_n = \mu_n\, kT/e$

-> $\sigma/(\varepsilon_0\varepsilon_r)\ \Delta n(x) = D_n\, \partial^2\Delta n/\partial x^2$

-> $\Delta n = \Delta n_0 \exp(-x/L)$ with Debye length $L=\sqrt{(D_n\tau)}$

and

$\partial\, \Delta n/\partial t = -1/\tau\, \Delta n$ -> $\Delta n \propto \exp(-t/\tau)$ where

$\tau = 10^{-10}$ s (doped Si) - 10^{-3} s (pure Si) for space charges

Fermi's golden rule for quantum-mechanically allowed transitions

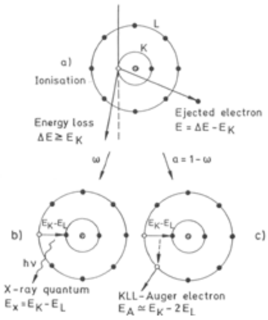
transition rate i–>f $\propto$ $N_i(E)$ $|M_{if}(E)|^2$ $N_f(E)$

density of initial states (here: in conduction band)

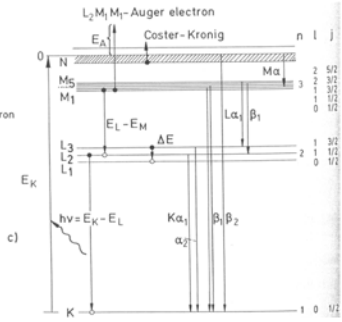
transition matrix with dipole selection rule

density of final states (here: in valence band)

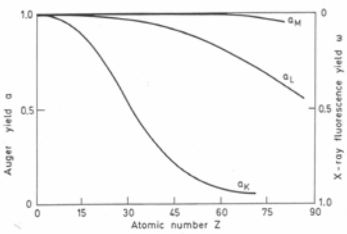
Radiative vs. Auger transitions



sketch of EELS (a), EDXS (b) and Auger electron emission (c)



selection rules for allowed transitions: $\Delta l = \pm 1$, $\Delta j = 0$ or ± 1



plot of Auger and X-ray fluorescence yield vs. atomic number

L. Reimer: Transmission Electron Microscopy, 2nd ed.(1989), Springer, Berlin, p.188-190

recombination probabilities

consider dependence of carrier lifetime on the minority charge carrier density *n*:

decay probability $\propto 1/\tau = A + Bn + Cn^2$ with some constants A,B,C

non-radiative contributions
due to defects, e.g. dislocations (L11, p23)

radiative recombinations of electrons and holes across band-gap, produces light (or X-rays)

non-radiative Auger recombination (3 electron process), produces free electrons