ECE606: Solid State Devices
Lecture 8

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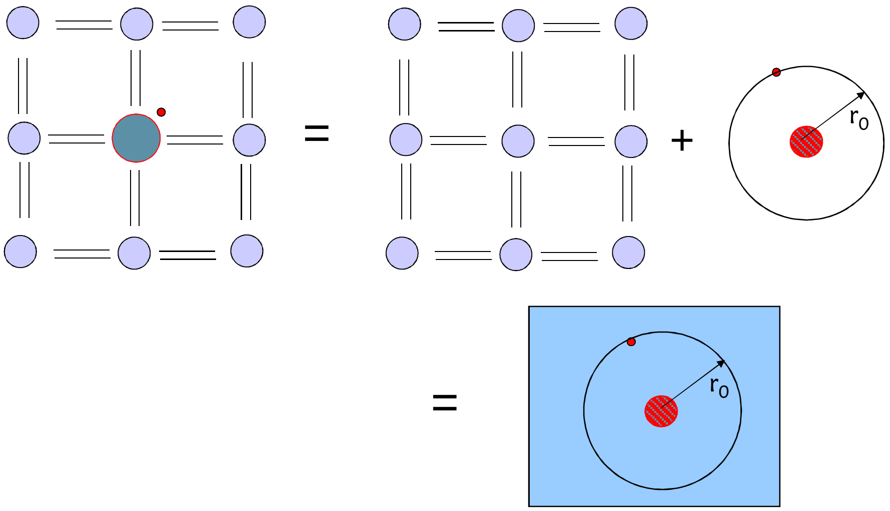
Presentation Outline

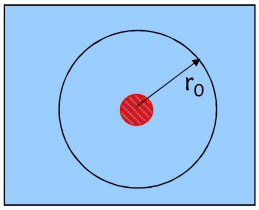
- Reminder:
  - »Basic concepts of donors and acceptors
  - »Statistics of donors and acceptor levels
  - »Intrinsic carrier concentration
- Temperature dependence of carrier concentration
- Multiple doping, co-doping, and heavy-doping
- Conclusion

Reference: Vol. 6, Ch. 4

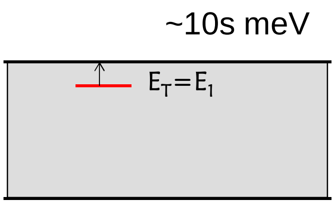
Donor Atoms in H2-analogy

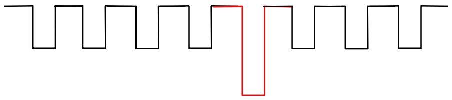


Donor Atoms in Real and Energy Space



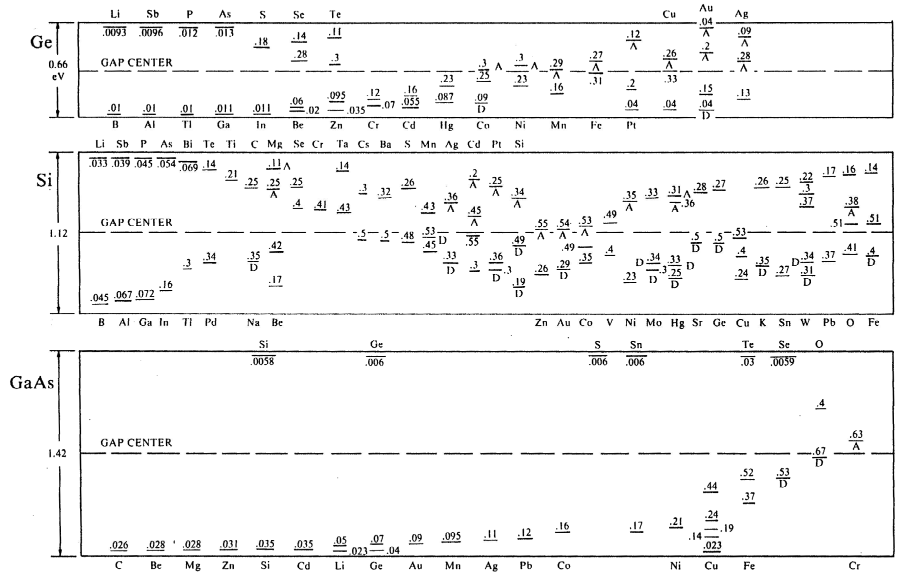
$$E_1 = -\frac{m^*_{host} q^4}{2\left(4\pi\varepsilon_0 K_{s,host}\hbar\right)^2} = -\frac{m_0 q^4}{2\left(4\pi\varepsilon_0\hbar\right)^2}\frac{m^*_{host}}{m_0}\frac{1}{K_{s,host}^2} = -13.6\times\frac{m^*_{host}}{m_0}\frac{1}{K_{s,host}^2}$$





$1/\beta \sim k_B T \sim 25$meV at T=300K

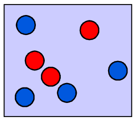
How to Read the Table …



Summary …

A bulk material must be charge neutral over all …

$$\int \left[p - n + N_D^+ + N_A^- \right] dV = 0$$



Further if the material is *spatially homogenous*

$$p - n + N_D^+ + N_A^- = 0$$

$$N_V e^{-(E_F - E_V)/k_B T} - N_A e^{-(E_C - E_F)/k_B T} + \frac{N_D}{1 + 2e^{(E_F - E_D)/k_B T}} - \frac{N_A}{1 + 4e^{(E_A - E_F)/k_B T}} = 0$$

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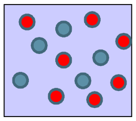
Carrier-density with Uniform Doping

A bulk material must be charge neutral over all …

$$\int \left[p - n + N_D^+ + N_A^- \right] dV = 0$$



Further if the doping is spatially homogenous

$$p - n + N_D^+ + N_A^- = 0$$

FD integral vs. FD function ?

$$N_V \frac{2}{\sqrt{\pi}} F_{1/2}\left[\beta\left(E_F - E_V\right)\right] - N_A \frac{2}{\sqrt{\pi}} F_{1/2}\left[\beta\left(E_C - E_F\right)\right] + \frac{N_D}{1+2e^{\beta(E_F - E_D)}} - \frac{N_A}{1+4e^{\beta(E_A - E_F)}} = 0$$

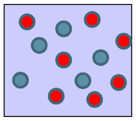
$$N_V e^{-(E_F - E_V)/k_B T} - N_A e^{-(E_C - E_F)/k_B T} + \frac{N_D}{1+2e^{(E_F - E_D)/k_B T}} - \frac{N_A}{1+4e^{(E_A - E_F)/k_B T}} = 0$$

(approx.)

Once you know E_F, you can calculate n, p, N_D^+, N_A^-.

Intrinsic Concentration

$$p - n + N_D^+ + N_A^- = 0$$



$$N_V e^{-(E_F-E_V)/k_BT} - N_C e^{-(E_C-E_F)/k_BT} + \cancel{\frac{N_D}{1+2e^{(E_F-E_D)/k_BT}}} - \cancel{\frac{N_A}{1+4e^{(E_A-E_F)/k_BT}}} = 0$$

$$n - p = 0 \Rightarrow N_C e^{-\beta(E_c-E_F)} = N_V e^{+\beta(E_v-E_F)}$$

$$E_F \equiv E_i = \frac{E_G}{2} + \frac{1}{2\beta} ln \frac{N_V}{N_C}$$

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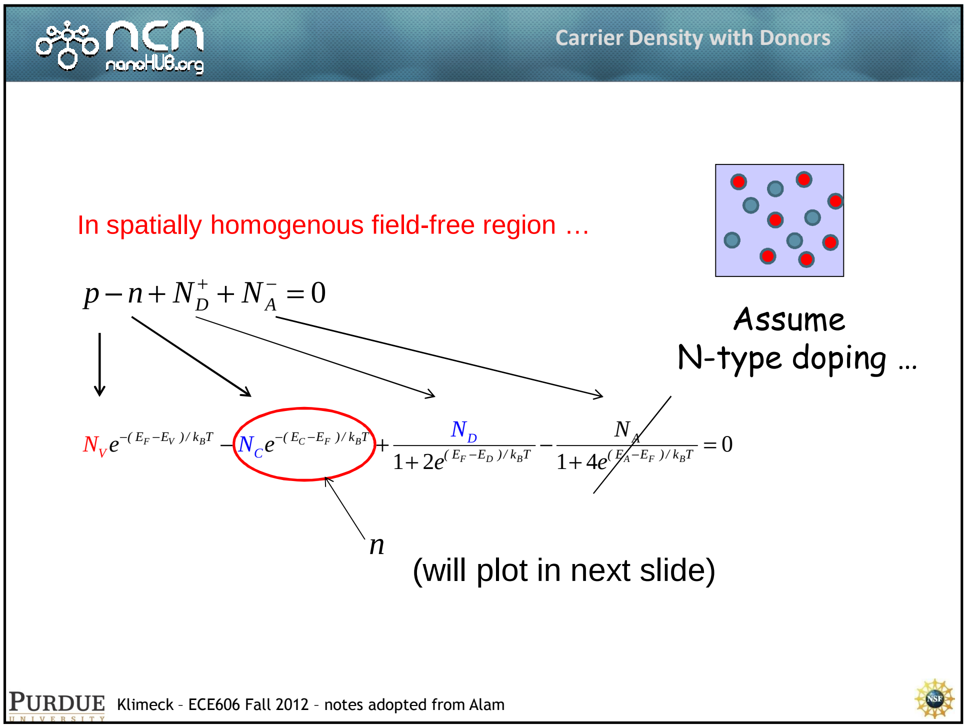


Carrier Density with Donors

In spatially homogenous field-free region …

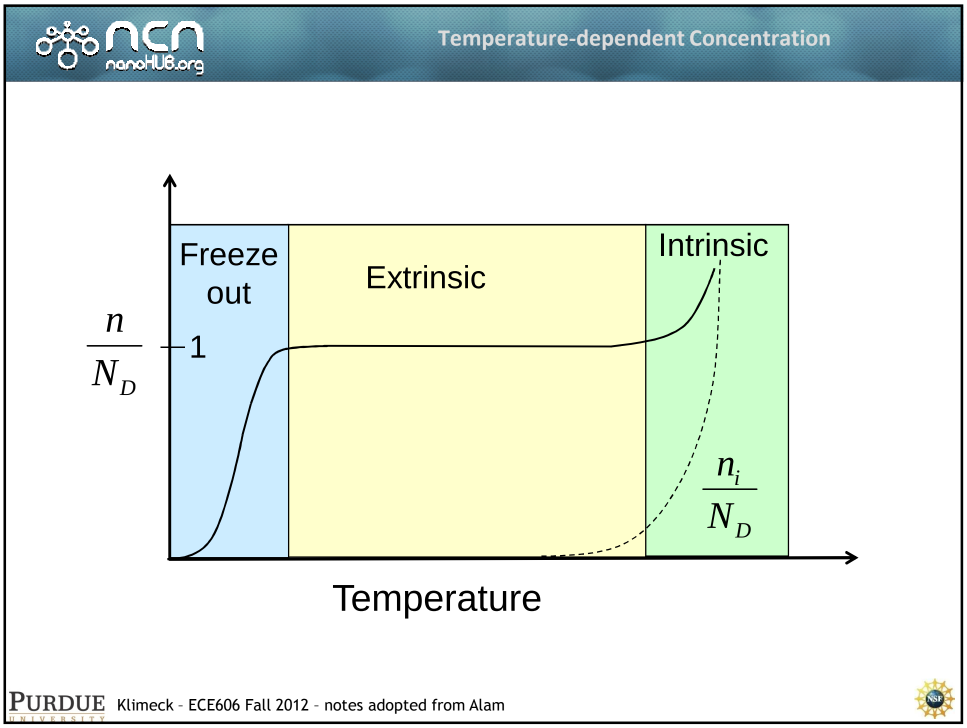
$$p - n + N_D^+ + N_A^- = 0$$

$$N_V e^{-(E_F-E_V)/k_BT} - N_C e^{-(E_C-E_F)/k_BT} + \frac{N_D}{1+2e^{(E_F-E_D)/k_BT}} - \cancel{\frac{N_A}{1+4e^{(E_A-E_F)/k_BT}}} = 0$$

n

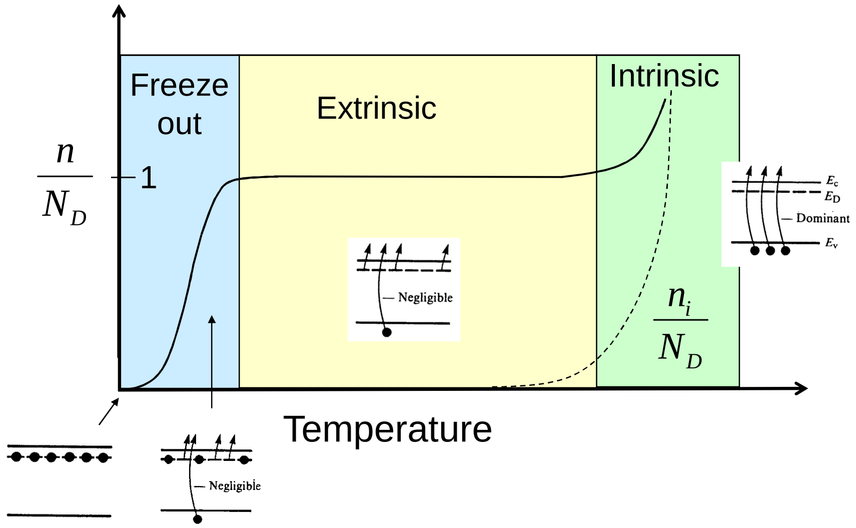
(will plot in next slide)

Assume
N-type doping …



Temperature-dependent Concentration

Physical Interpretation

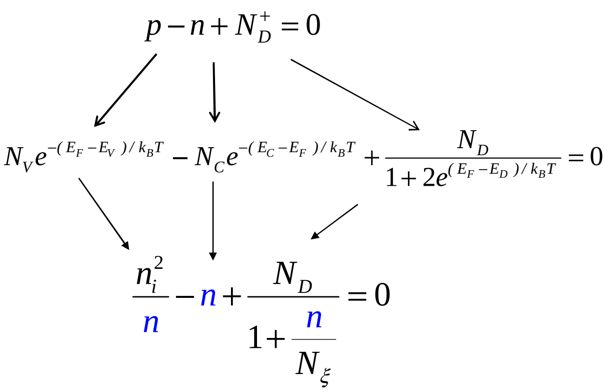


Electron Concentration with Donors

$$n = N_C e^{-\beta(E_C - E_F)} \Rightarrow \frac{n}{N_C} e^{\beta E_C} = e^{\beta E_F}$$

$$N_D^+ = \frac{N_D}{1+2e^{\beta(E_F - E_D)}} = \frac{N_D}{1+2\left[\frac{n}{N_C} e^{\beta(E_c - E_D)}\right]} \equiv \frac{N_D}{1+\frac{n}{N_\xi}}$$

Electron concentration with Donors



$$p - n + N_D^+ = 0$$

$$N_V e^{-(E_F - E_V)/k_BT} - N_C e^{-(E_C - E_F)/k_BT} + \frac{N_D}{1 + 2e^{(E_F - E_D)/k_BT}} = 0$$

$$p \times n = n_i^2$$

$$\frac{n_i^2}{n} - n + \frac{N_D}{1 + \frac{n}{N_\xi}} = 0$$

No approximation so far ….

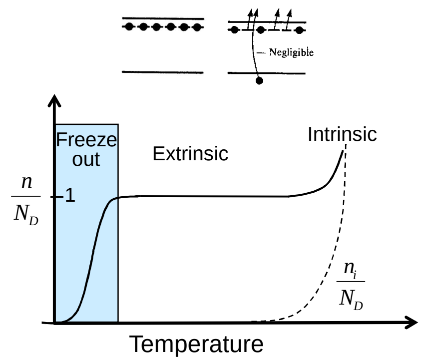
High Donor density/Freeze out T

$$\frac{n_i^2}{n} - n + \frac{N_D}{1 + \frac{n}{N_\xi}} = 0$$

$$N_D \gg n_i$$

$$\Rightarrow -n + \frac{N_D}{1 + \frac{n}{N_\xi}} \approx 0$$

$$\Rightarrow n^2 + N_\xi n - N_\xi N_D = 0$$



$$N_\xi \equiv \frac{N_C}{2} e^{-\beta(E_C - E_D)}$$

$$n = \frac{N_\xi}{2}\left[\left(1 + \frac{4N_D}{N_\xi}\right)^{1/2} - 1\right]$$

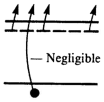
Extrinsic T

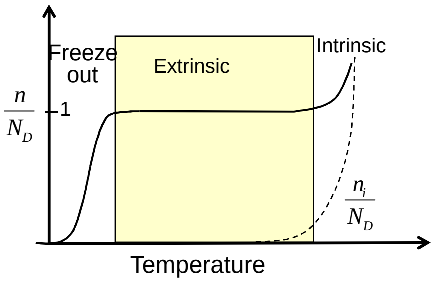
$$N_\xi \equiv \frac{N_C}{2} e^{-(E_C-E_D)/kT} \gg N_D$$

$$n = \frac{N_\xi}{2}\left[\left(1+\frac{4N_D}{N_\xi}\right)^{1/2}-1\right]$$

$$\approx \frac{\cancel{N_\xi}}{2}\left[\left(\cancel{1}+\frac{1}{2}\frac{4N_D}{\cancel{N_\xi}}\right)-\cancel{1}\right]$$

$$\approx N_D$$





Electron concentration equals donor density
hole concentration by nxp=n_i^2

Intrinsic T

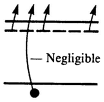
$$N_D^+ = \frac{N_D}{1+2e^{(E_F-E_D)/k_BT}} \approx N_D \quad \text{for } E_F < E_D$$

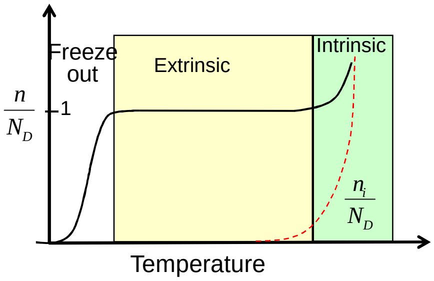
0

$$\frac{n_i^2}{n} - n + \frac{N_D}{1+\frac{n}{N_\xi}} = 0$$

$$\frac{n_i^2}{n} - n + N_D \approx 0$$

$$\Rightarrow -n_i^2 + n^2 - N_D n = 0$$





$$n = \frac{N_D}{2} + \left[\frac{N_D{}^2}{4} + n_i^2\right]^{1/2}$$

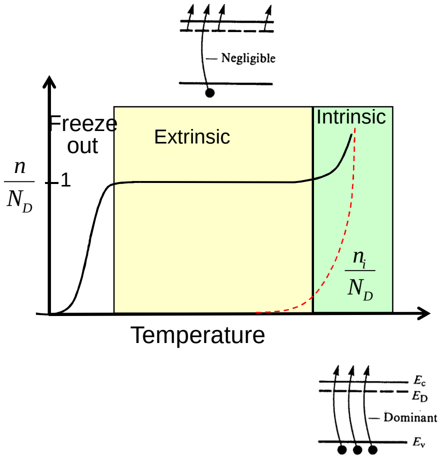
Extrinsic/Intrinsic T

For $N_D \gg n_i$

$$n = \frac{N_D}{2} + \left[\frac{N_D{}^2}{4} + n_i^2 \right]^{1/2} \approx N_D$$

For $n_i \gg N_D$

$$n = \frac{N_D}{2} + \left[\frac{N_D{}^2}{4} + n_i^2 \right]^{1/2} \approx n_i$$



What will happen if you use silicon circuits at very high temperatures ?
Bandgap determines the intrinsic carrier density.

Determination of Fermi-level

$$n = N_C e^{-\beta(E_c - E_F)} \Rightarrow E_F = E_C + \frac{1}{\beta} ln\left(\frac{n}{N_C}\right)$$

$$p - n + N_D^+ = 0$$

$$N_V e^{-(E_F - E_V)/k_B T} - N_C e^{-(E_C - E_F)/k_B T} + \frac{N_D}{1 + 2e^{(E_F - E_D)/k_B T}} = 0$$

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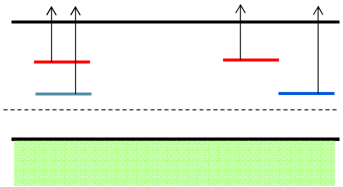
Multiple Donor Levels



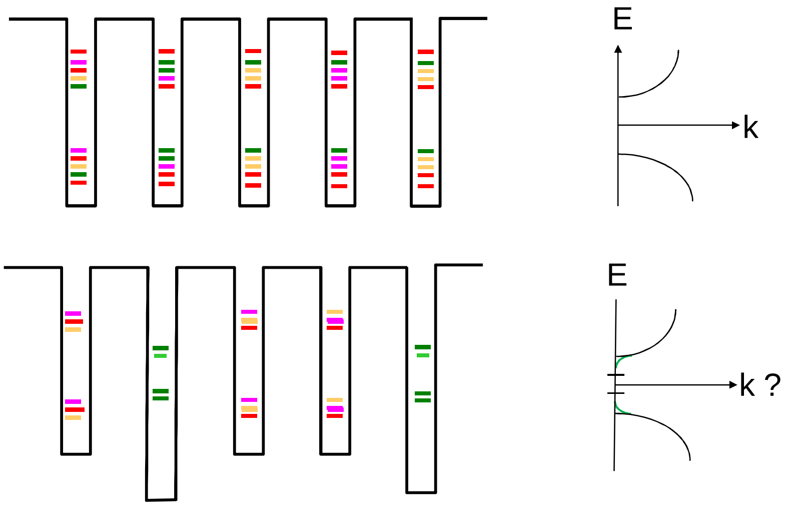
Multiple levels of same donor …

$$p-n+\frac{N_D}{1+2e^{(E_F-E_{D1})/k_BT}}+\frac{N_D}{1+2e^{(E_F-E_{D2})/k_BT}}-\frac{N_A}{1+4e^{(E_A-E_F)/k_BT}}=0$$

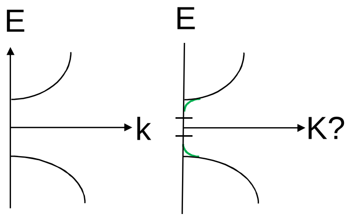
Codoping…

$$p-n+\frac{N_{D1}}{1+2e^{(E_F-E_{D1})/k_BT}}+\frac{N_{D2}}{1+2e^{(E_F-E_{D2})/k_BT}}-\frac{N_A}{1+4e^{(E_A-E_F)/k_BT}}=0$$

Heavy Doping Effects: Bandtail States



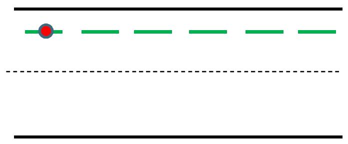
Heavy Doping Effects: Hopping Conduction



Bandgap narrowing

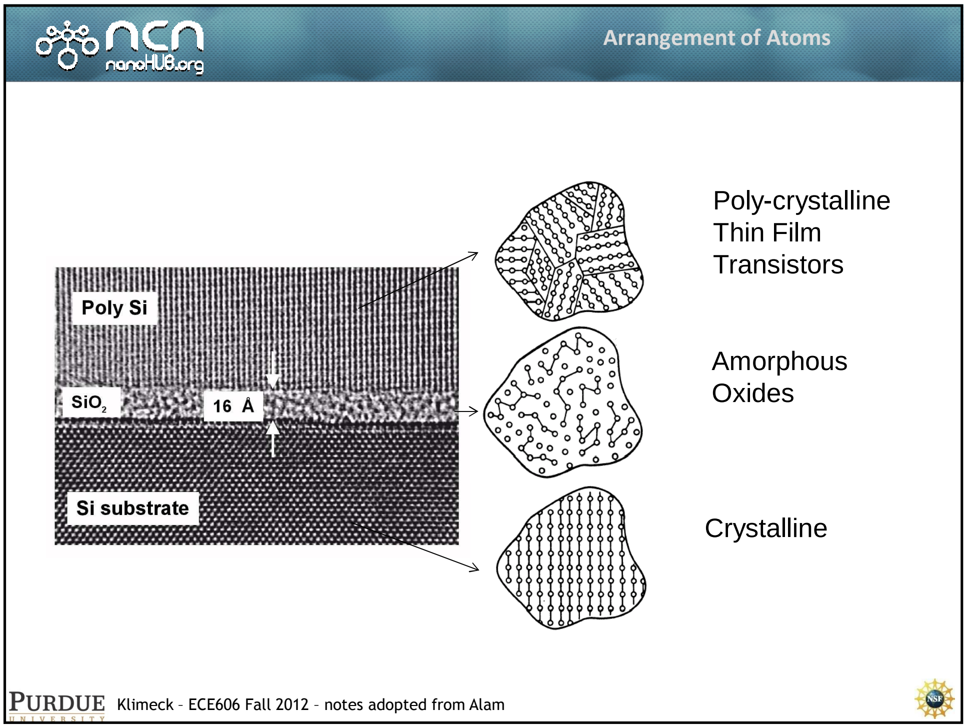
$$p \times n = N_C N_V e^{-\beta E_G^*}$$

e.g. Base of HBTs



Band transport
vs.
hopping-transport

e.g. a-silicon, OLED

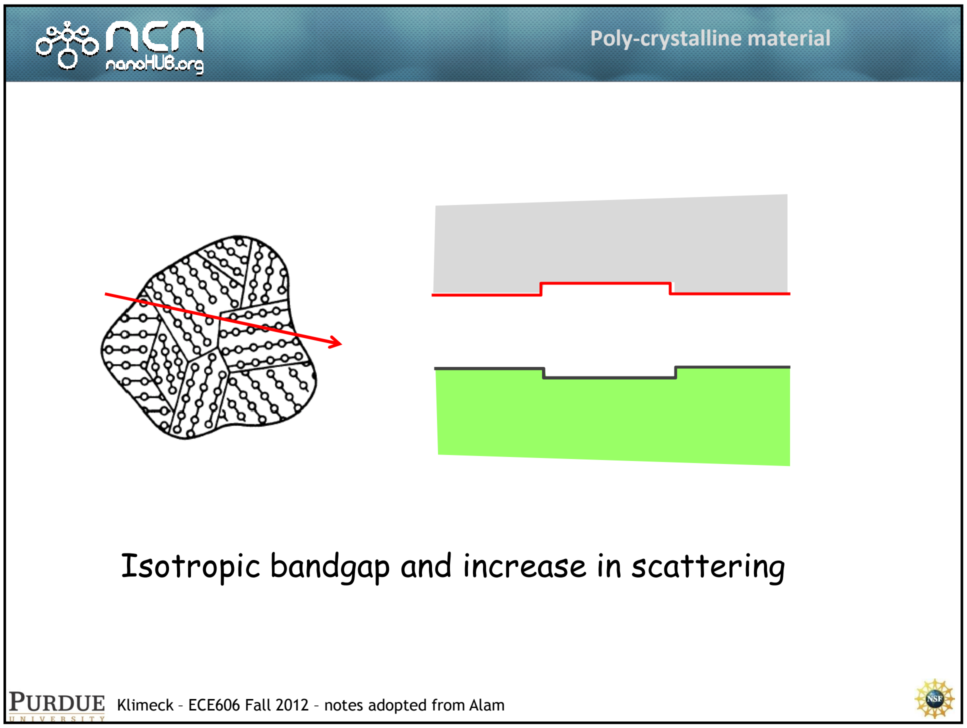


Arrangement of Atoms

Poly-crystalline
Thin Film
Transistors

Amorphous
Oxides

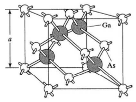
Crystalline



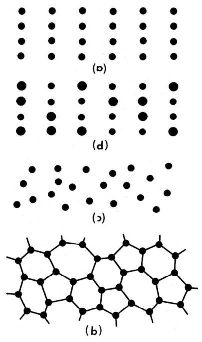
Poly-crystalline material

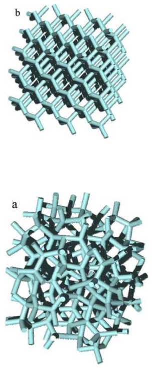
Isotropic bandgap and increase in scattering

Band-structure and Periodicity



PRB, 4, 2508, 1971





Edagawa, PRL, 100,013901, 2008

Periodicity is sufficient, but not necessary for bandgap.
Many amorphous material show full isotropic bandgap

Conclusions

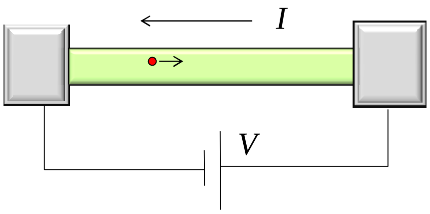
1. Charge neutrality condition and law of mass-action allows calculation of Fermi-level and all carrier concentration.
2. For semiconductors with field, charge neutrality will not hold and we will need to use Poisson equation.
3. Heaving doping effects play an important role in carrier transport.

Outline

1) **Non-equilibrium systems**
2) Recombination generation events
3) Steady-state and transient response
4) Derivation of R-G formula
5) Conclusion

Ref. Chapter 5, pp. 134-146

Current Flow Through Semiconductors



$$I = G \times V$$

$$= q \times n \times v \times A$$

Carrier Density

velocity

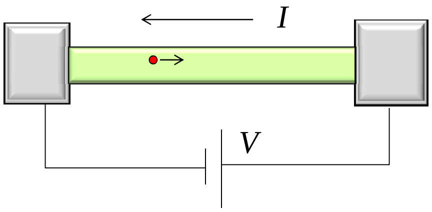
Depends on chemical composition, crystal structure, temperature, doping, etc.

Quantum Mechanics + Equilibrium Statistical Mechanics
⇒ Encapsulated into concepts of effective masses and occupation factors (Ch. 1-4)

Transport with scattering, non-equilibrium Statistical Mechanics
⇒ Encapsulated into drift-diffusion equation with recombination-generation (Ch. 5 & 6)

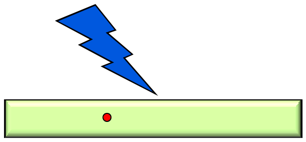
Non-equilibrium Systems

Chapter 6



vs.

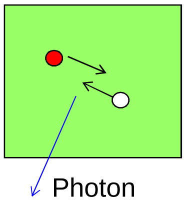
Chapter 5



How does the system go BACK to equilibrium?

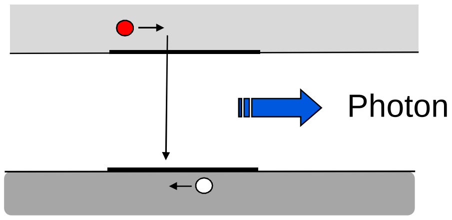
Direct Band-to-band Recombination

In real space …



e and h must
have same wavelength
1 in 1,000,000 encounters

In energy space …



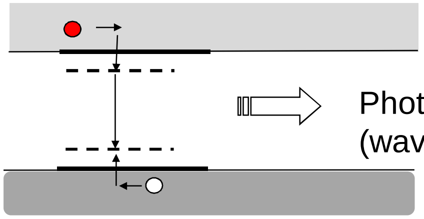
Direct transistion –
direct gap material

GaAs, InP, InSb (3D)

Lasers, LEDs, etc.

Direct Excitonic Recombination

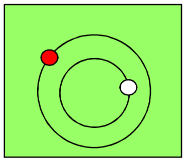
In energy space …



Mostly in 1D systems
Requires strong coulomb interactions

Photon
(wavelength reduced from bulk)

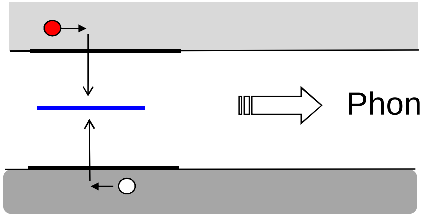
In real space …



CNT, InP, ID-systems

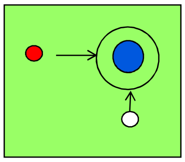
Transistors, Lasers, Solar cells, etc.

Indirect Recombination (Trap-assisted)



Phonon

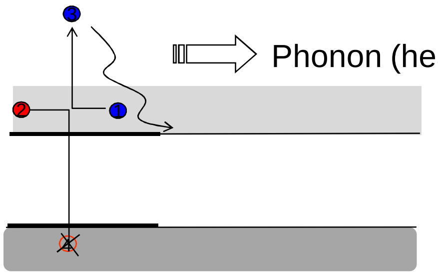
Trap needs to be mid-gap to be effective.
Cu or Au in Si



Ge, Si, ….

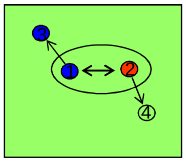
Transistors, Solar cells, etc.

Auger Recombination



Phonon (heat)

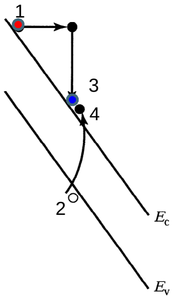
Requires very high electron density

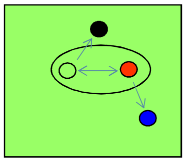


InP, GaAs, …

Lasers, etc.

Impact Ionization - A Generation Mechanism

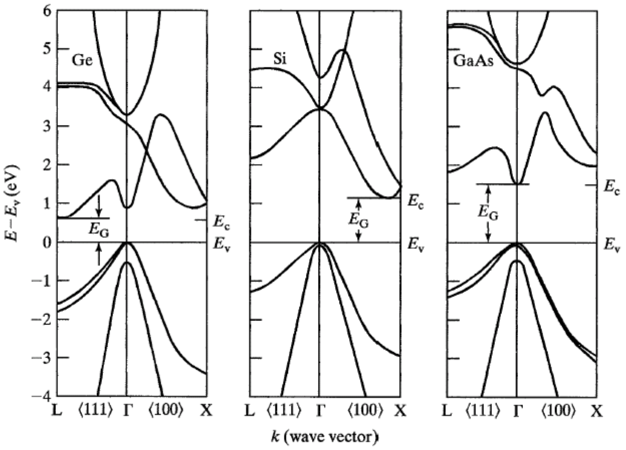




Si, Ge, InP

Lasers, Transistors, etc.

Indirect vs. Direct Bandgap



The top & bottom of bands do not align at same wavevector k for indirect bandgap material

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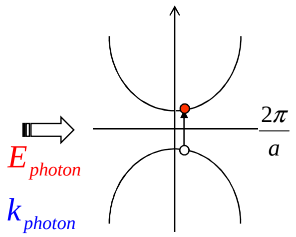
Photon Energy and Wavevector



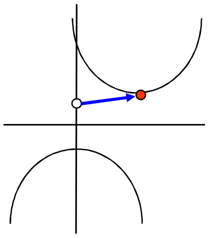
$$E_V + E_{photon} = E_C$$

$$\hbar k_V + \hbar k_{photon} = \hbar k_C$$

$$k_{photon} = \frac{2\pi}{\lambda \text{ in } \mu\text{m}} = \frac{2\pi}{1.21/E_{photon} \text{ in eV}} \quad \boxed{<< \frac{2\pi}{a} = \frac{2\pi}{5\times10^{-4}\ \mu\text{m}}}$$

Photon has large energy for excitation through bandgap, but its wavevector is negligible compared to size of BZ

Phonon Energy and Wavevector



$$E_V + E_{phonon} = E_C$$

$$\hbar k_V + \hbar k_{phonon} = \hbar k_C$$

v_{sound} ~ 10^3 m/s << v_{light}=c ~ 10^6m/s

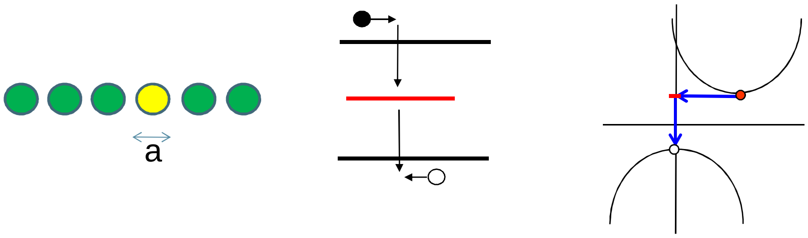
λ^{sound} >> λ^{light}

$$k_{phonon} = \frac{2\pi}{\lambda} = \frac{2\pi}{\hbar \upsilon_{sound} / E_{phonon}} \approx \frac{2\pi}{a} = \frac{2\pi}{5\times10^{-4}\ \mu\mathrm{m}}$$

Phonon has large wavevector comparable to BZ, but negligible energy compared to bandgap

---

Localized Traps and Wavevector



$$k_{trap} \approx \frac{2\pi}{a} \sim \frac{2\pi}{5\times10^{-4}\ \mu m}$$

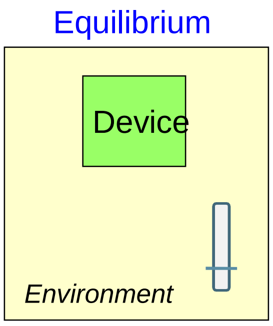
Trap provides the wavevector necessary for indirect transition

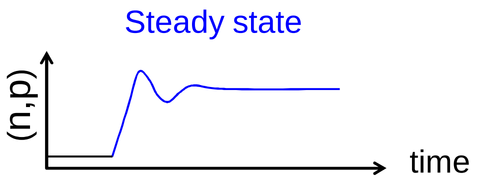
Outline

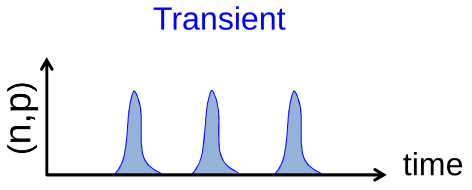
1) Non-equilibrium systems
2) Recombination generation events
3) **Steady-state and transient response**
4) Derivation of R-G formula
5) Conclusion

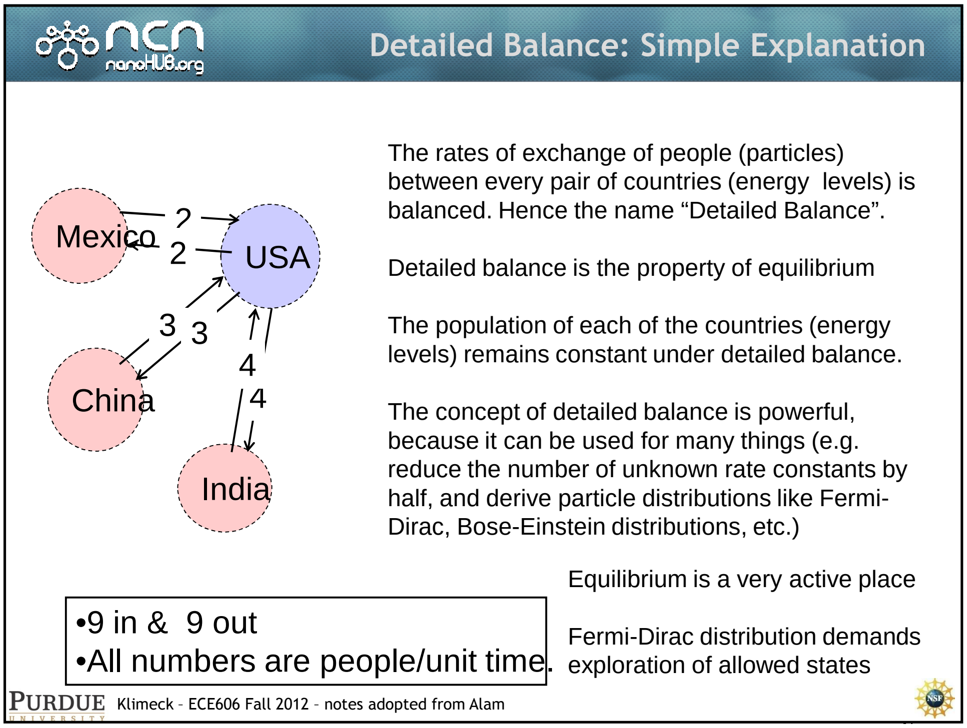
Ref. Chapter 5, pp. 134-146

Equilibrium, Steady state, Transient









Detailed Balance: Simple Explanation

The rates of exchange of people (particles) between every pair of countries (energy levels) is balanced. Hence the name “Detailed Balance”.

Detailed balance is the property of equilibrium

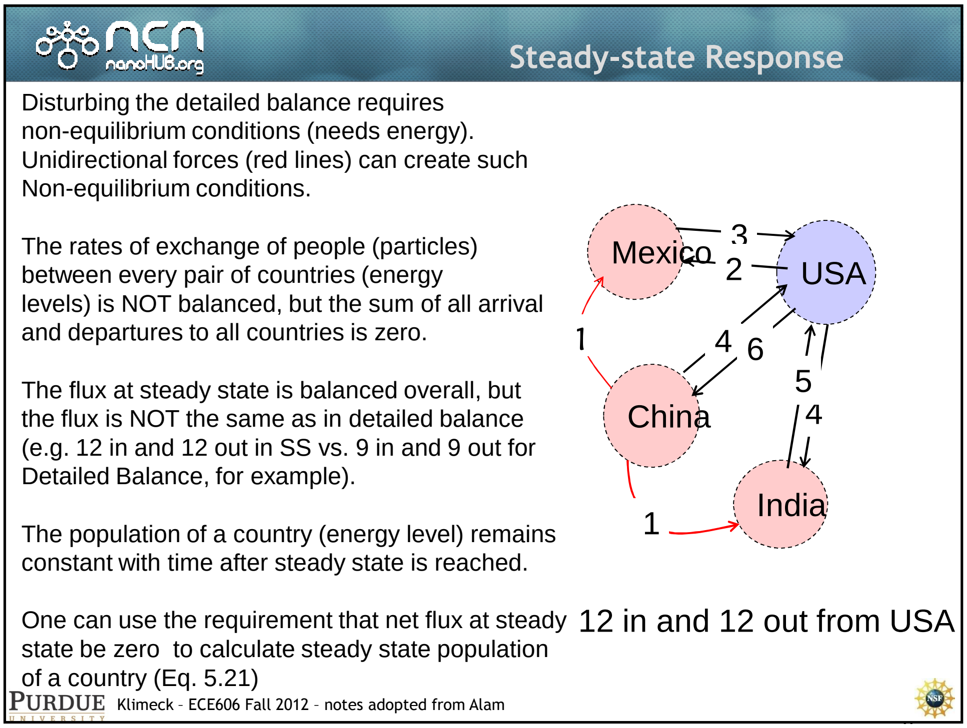
The population of each of the countries (energy levels) remains constant under detailed balance.

The concept of detailed balance is powerful, because it can be used for many things (e.g. reduce the number of unknown rate constants by half, and derive particle distributions like Fermi-Dirac, Bose-Einstein distributions, etc.)

- 9 in & 9 out
- All numbers are people/unit time.

Equilibrium is a very active place

Fermi-Dirac distribution demands exploration of allowed states



Steady-state Response

Disturbing the detailed balance requires non-equilibrium conditions (needs energy). Unidirectional forces (red lines) can create such Non-equilibrium conditions.

The rates of exchange of people (particles) between every pair of countries (energy levels) is NOT balanced, but the sum of all arrival and departures to all countries is zero.

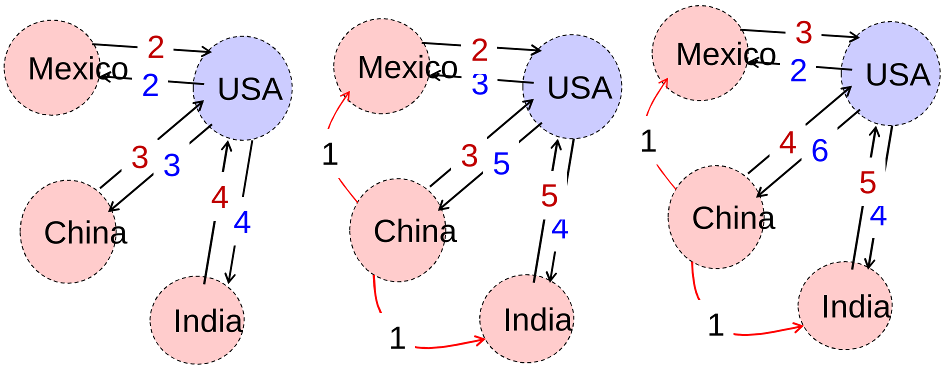
The flux at steady state is balanced overall, but the flux is NOT the same as in detailed balance (e.g. 12 in and 12 out in SS vs. 9 in and 9 out for Detailed Balance, for example).

The population of a country (energy level) remains constant with time after steady state is reached.

One can use the requirement that net flux at steady state be zero to calculate steady state population of a country (Eq. 5.21)

12 in and 12 out from USA

Detailed Balance, Transient, Steady-state



9 in 9 out
Population conserved

Equilibrium =
Detailed balance

Forced unidirectional connections
(red lines) disturbs equilibrium
(e.g. 10 in/12 out at time t1
local populations not conserved,
but global population is ….

Transient populations

12 in 12 out
Population stabilized

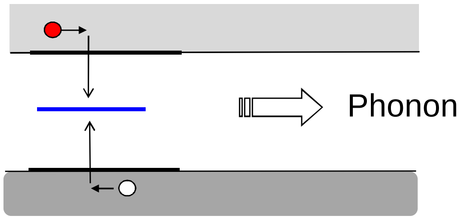
Steady State
But NOT Equilibrium

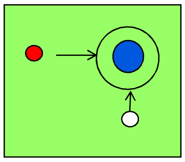
Outline

1) Non-equilibrium systems
2) Recombination generation events
3) Steady-state and transient response
4) **Derivation of R-G formula**
5) Conclusion

Ref. Chapter 5, pp. 134-146

Indirect Recombination (Trap-assisted)





Ge, Si, ….

Transistors, Solar cells, etc.

Physical view of Carrier Capture/Recombination

● electron

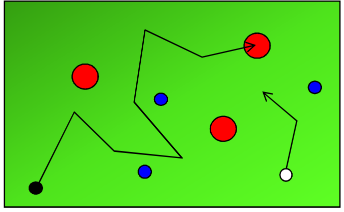
○ hole

🟩 Crystal / atoms with vibrations

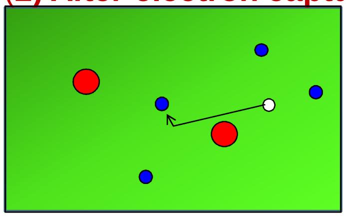
total traps | electron-filled traps | empty traps

$$N_T = n_T + p_T$$

(1) Before a capture



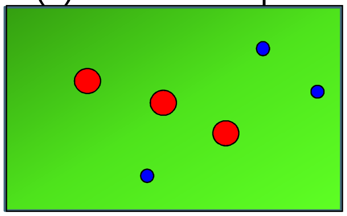
(2) After electron capture

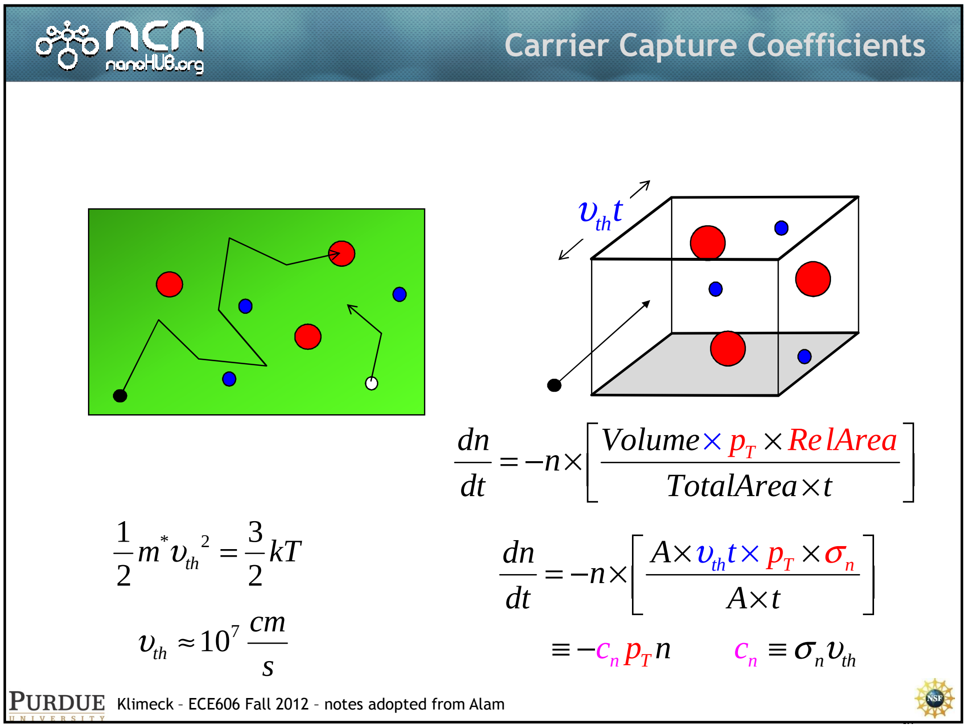


Traps have destroyed one electron-hole pair

No change in n_T and p_T

(3) After hole capture





Carrier Capture Coefficients

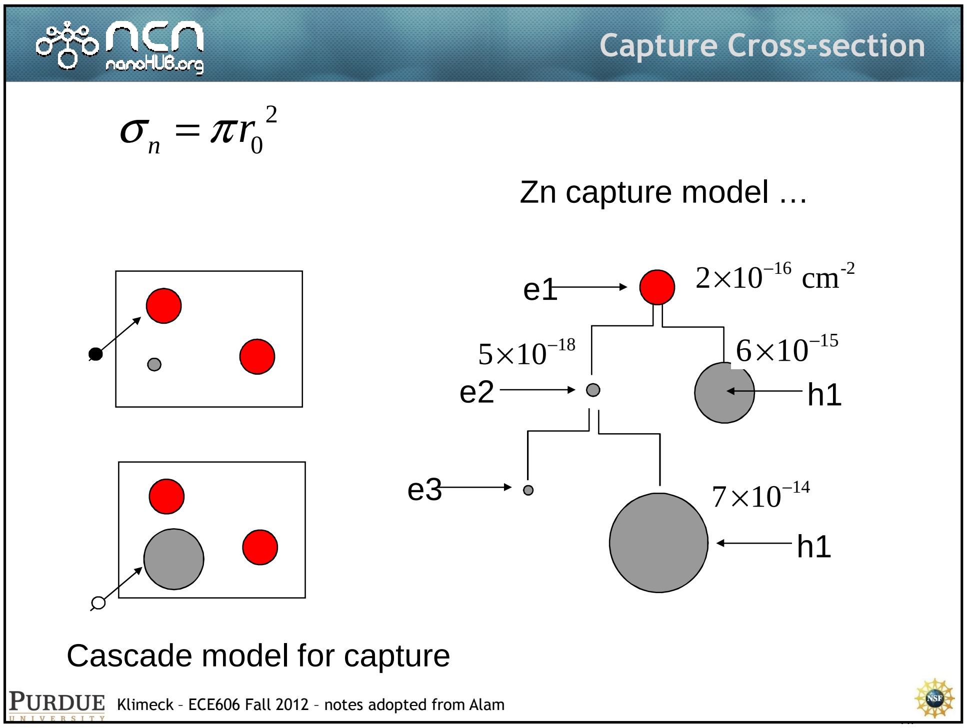
$$\frac{dn}{dt} = -n\times\left[\frac{Volume\times p_T\times Re\,lArea}{TotalArea\times t}\right]$$

$$\frac{1}{2}m^*\upsilon_{th}^{\ 2} = \frac{3}{2}kT$$

$$\upsilon_{th}\approx 10^7\,\frac{cm}{s}$$

$$\frac{dn}{dt} = -n\times\left[\frac{A\times\upsilon_{th}t\times p_T\times\sigma_n}{A\times t}\right]$$

$$\equiv -c_n p_T n \qquad c_n\equiv\sigma_n\upsilon_{th}$$



Capture Cross-section

$$\sigma_n = \pi r_0^{\ 2}$$

Zn capture model …

Cascade model for capture

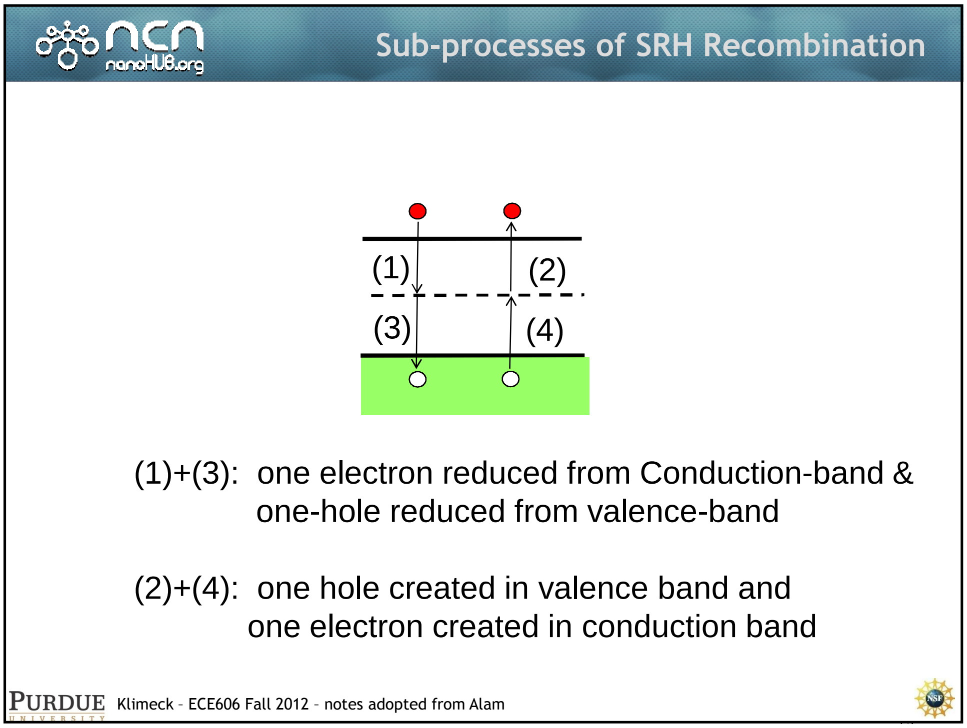
Conclusions

1) There are wide variety of generation-recombination events that allow restoration of equilibrium once the stimulus is removed.
2) Direct recombination is photon-assisted, indirect recombination phonon assisted.
3) Concepts of equilibrium, steady state, and transient dynamics should be clearly understood.

Outline

1) **Derivation of SRH formula**
2) Application of SRH formula for special cases
3) Direct and Auger recombination
4) Conclusion

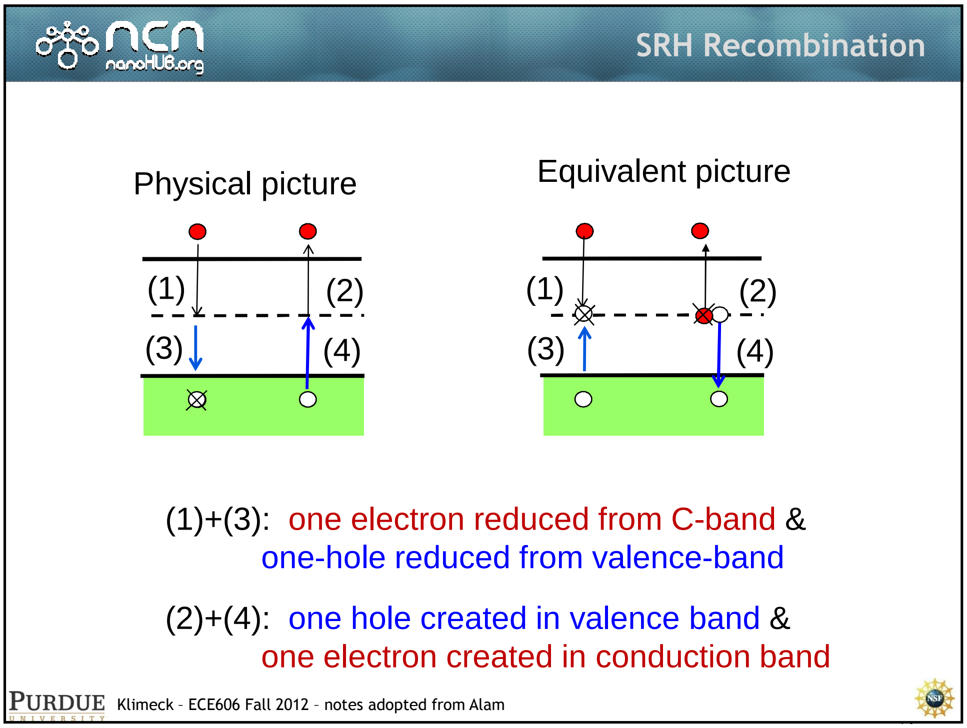
Ref. ADF, Chapter 5, pp. 141-154



Sub-processes of SRH Recombination

(1)+(3): one electron reduced from Conduction-band &
one-hole reduced from valence-band

(2)+(4): one hole created in valence band and
one electron created in conduction band

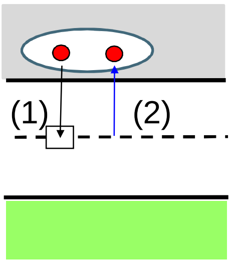


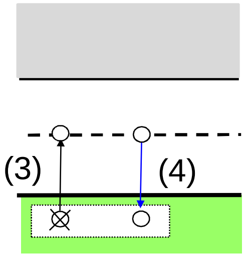
SRH Recombination

(1)+(3): one electron reduced from C-band &
one-hole reduced from valence-band

(2)+(4): one hole created in valence band &
one electron created in conduction band

Changes in electron and hole Densities

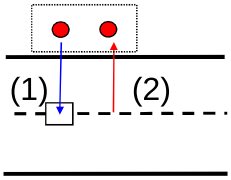


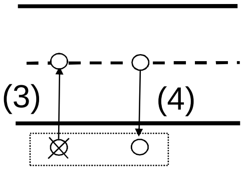


$$\left.\frac{\partial n}{\partial t}\right|_{1,2} = -c_n\, n\, p_T + e_n n_T \left(1 - f_c\right)$$

$$\left.\frac{\partial p}{\partial t}\right|_{3,4} = -c_p\, p\, n_T + e_p\, p_T\, f_\upsilon$$

Detailed Balance in *Equilibrium*





$\left(1 - f_c\right) \approx 1$ Assume non-degenerate

$$\left.\frac{\partial n}{\partial t}\right|_{1,2} = -c_n\, n_0\, p_{T0} + e_n n_{T0}$$

$$0 = -c_n n_0 p_{T0} + e_n n_{T0}$$

$$e_n = c_n \frac{n_0 p_{T0}}{n_{T0}} \equiv c_n n_1$$

$$0 = -c_n \left(n_0 p_{T0} - n_{T0} n_1\right)$$

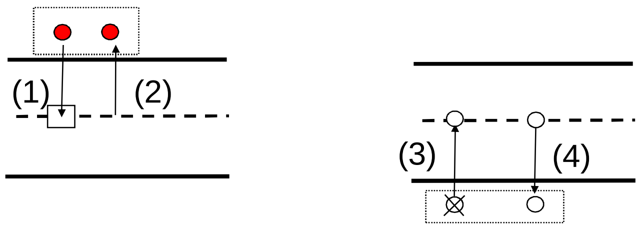
$$\left.\frac{\partial p}{\partial t}\right|_{3,4} = -c_p\, p\, n_T + e_p\, p_T$$

$$0 = -c_p p_0 n_{T0} + p_{T0} e_p$$

$$e_p \equiv \frac{c_p p_0 n_{T0}}{p_{T0}} = c_p p_1$$

$$0 = -c_p \left(p_0 n_{T0} - p_{T0} p_1\right)$$

Expressions for (n_1) and (p_1)

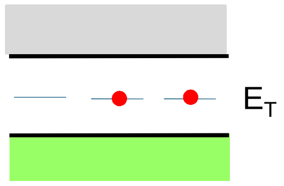


$$n_1 = \frac{n_0 p_{T0}}{n_{T0}} \qquad\qquad p_1 = \frac{p_0 n_{T0}}{p_{T0}}$$

$$n_1 p_1 = \frac{n_0 p_{T0}}{n_{T0}} \times \frac{p_0 n_{T0}}{p_{T0}} = n_0 p_0 = n_i^2$$

Expressions for (n_1) and (p_1)

Trap is like a donor!



$$n_{T0} = N_T\left(1 - f_{00}\right) = \frac{N_T}{1 + g_D e^{\beta(E_T - E_F)}}$$

$$\left(1 - f_{00}\right) = \frac{1}{1 + g\,exp} \qquad f_{00} = 1 - \frac{1}{1 + g\,exp}$$

$$f_{00} = \frac{g\,exp}{1 + g\,exp} \qquad f_{00}\big/1 - f_{00} = \frac{g\,exp}{1 + g\,exp} \Big/ \frac{1}{1 + g\,exp} = g\,exp$$

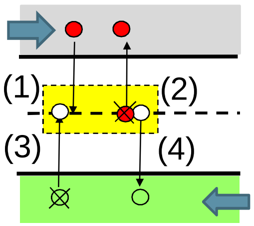
$$n_1 = \frac{n_0 p_{T0}}{n_{T0}} \quad = n_0 \frac{\left(N_T f_{00}\right)}{N_T\left(1 - f_{00}\right)}$$

$$p_1 n_1 = n_i^2$$

$$n_1 = n_i e^{\beta(E_F - E_i)} g_D e^{\beta(E_T - E_F)}$$
$$= n_i g_D e^{\beta(E_T - E_i)}$$

$$p_1 = n_i^2 \big/ n_1$$
$$= n_i g_D{}^{-1} e^{\beta(E_i - E_T)}$$

Dynamics of Trap Population

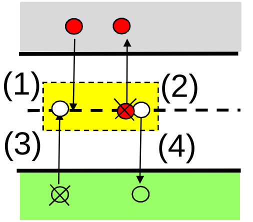


$$\frac{\partial n_T}{\partial t} = -\left.\frac{\partial n}{\partial t}\right|_{1,2} + \left.\frac{\partial p}{\partial t}\right|_{3,4}$$

$$= c_n\, n\, p_T \;- e_n n_T \;- c_p\, p\, n_T \;+ e_p\, p_T$$

$$= c_n\left(np_T - n_T n_1\right) - c_p\left(p\, n_T - p_T\, p_1\right)$$

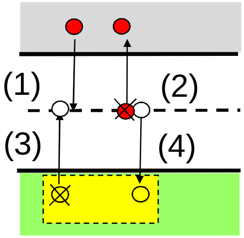
Steady-state Trap Population



$$\frac{\partial n_T}{\partial t} = 0 \;= c_n\left(np_T - n_T n_1\right) - c_p\left(p\, n_T - p_T\, p_1\right)$$

$$n_T = \frac{c_n N_T n + c_p N_T p_1}{c_n\left(n + n_1\right) + c_p\left(p + p_1\right)} = c_n\left(np_T - n_T n_1\right)$$

Net Rate of Recombination-Generation



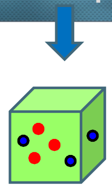
$$R = -\frac{dp}{dt} = c_p \left(p\, n_T - p_T\, p_1 \right)$$

$$= \frac{np - n_i^2}{\underbrace{\left(\frac{1}{c_p N_T}\right)}_{\tau_n}(n+n_1) + \underbrace{\left(\frac{1}{c_n N_T}\right)}_{\tau_p}(p+p_1)}$$

Outline

1) Derivation of SRH formula
2) **Application of SRH formula for special cases**
3) Direct and Auger recombination
4) Conclusion

Case 1: Low-level Injection in p-type



$$R = \frac{np - n_i^2}{\tau_p\left(n + n_1\right) + \tau_n\left(p + p_1\right)}$$

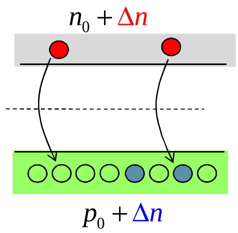
$$= \frac{\left(n_0 + \Delta n\right)\left(p_0 + \Delta n\right) - n_i^2}{\tau_p\left(n_0 + \Delta n + n_1\right) + \tau_n\left(p_0 + \Delta p + p_1\right)}$$

$$= \frac{\Delta n\left(n_0 + p_0\right) + \cancel{\Delta n^2}}{\tau_p\left(\cancel{n_0} + \Delta n + n_1\right) + \tau_n\left(p_0 + \Delta p + p_1\right)}$$

$$= \frac{\Delta n\left(p_0\right)}{\tau_n\left(p_0\right)} = \frac{\Delta n}{\tau_n}$$

$$\Delta n^2 \approx 0$$

$$p_0 \gg \Delta n \gg n_0$$



Lots of holes, few electrons => independent of holes

Case 2: High-level Injection

$$R = \frac{np - n_i^2}{\tau_p\left(n + n_1\right) + \tau_n\left(p + p_1\right)}$$

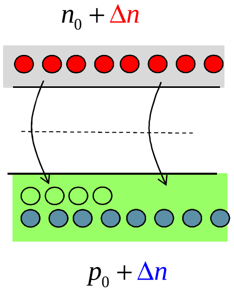
e.g. organic solar cells

$$= \frac{\left(n_0 + \Delta n\right)\left(p_0 + \Delta p\right) - n_i^2}{\tau_p\left(n_0 + \Delta n + n_1\right) + \tau_n\left(p_0 + \Delta p + p_1\right)}$$

$$= \frac{\cancel{\Delta n}\left(n_0 + p_0\right) + \Delta n^2}{\tau_p\left(\cancel{n_0} + \Delta n + n_1\right) + \tau_n\left(\cancel{p_0} + \Delta n + p_1\right)}$$

$$= \frac{\Delta n^2}{\left(\tau_n + \tau_p\right)\Delta n} = \frac{\Delta n}{\left(\tau_n + \tau_p\right)}$$

$$\Delta n \gg p_0 \gg n_0$$



Lots of holes, lots of electrons => dependent on both relaxations

High/Low Level Injection …

$$R_{high} = \frac{\Delta n}{\left(\tau_n + \tau_p\right)} \qquad \Delta n \gg p_0 \gg n_0$$

$$R_{low} = \frac{\Delta n}{\tau_p} \qquad p_0 \gg \Delta n \gg n_0$$

which one is larger and why?

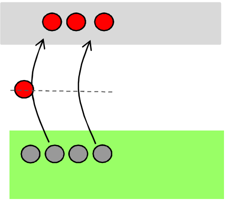
Case 3: Generation in Depletion Region

Depletion region – in PN diode: n=p=0

$$n \ll n_1 \qquad p \ll p_1$$

$$R = \frac{n\cancel{p} - n_i^2}{\tau_p\left(\cancel{n} + n_1\right) + \tau_n\left(\cancel{p} + p_1\right)}$$

$$= \frac{-n_i^2}{\tau_p\left(n_1\right) + \tau_n\left(p_1\right)}$$



NEGATIVE Recombination => Generation

n=p=0 << n_i => generation to create n,p

Equilibrium restoration!

Outline

1) Derivation of SRH formula
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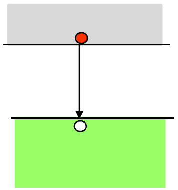
3) **Direct and Auger recombination**
4) Conclusion

Band-to-band Recombination



$$R = B\left(np - n_i^2\right)$$ B is a material property

Direct recombination at low-level injection

$$n_0 \ll \left(\Delta n = \Delta p\right) \ll p_0$$

$$R = B\left[\left(n_0 + \Delta n\right)\left(p_0 + \Delta p\right) - n_i^2\right] \approx Bp_0 \times \Delta n$$

Direct generation in depletion region

$$n, p \sim 0$$

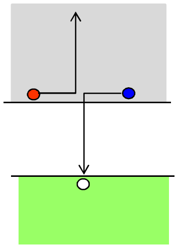
$$R = B\left(np - n_i^2\right) \approx -Bn_i^2$$

Auger Recombination

2 electron & 1 hole

$$R = c_n\left(n^2 p - n_i^2 n\right) + c_p\left(np^2 - n_i^2 p\right)$$

$$c_n, c_p \sim 10^{-29}\ \text{cm}^6/\text{sec}$$

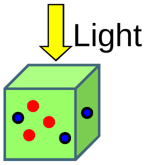


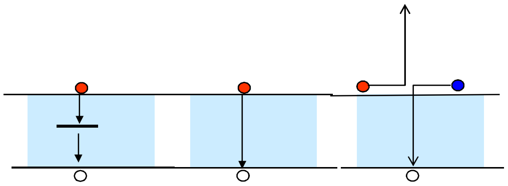
Auger recombination at low-level injection

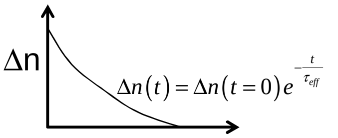
$$n_0 \ll (\Delta n = \Delta p) \ll (p_0 = N_A)$$

$$R \approx c_p N_A^2 \Delta n = \frac{\Delta n}{\tau_{auger}} \qquad \tau_{auger} = \frac{1}{c_p N_A^2}$$

Effective Carrier Lifetime







$$\Delta n(t) = \Delta n(t=0)e^{-\frac{t}{\tau_{eff}}}$$

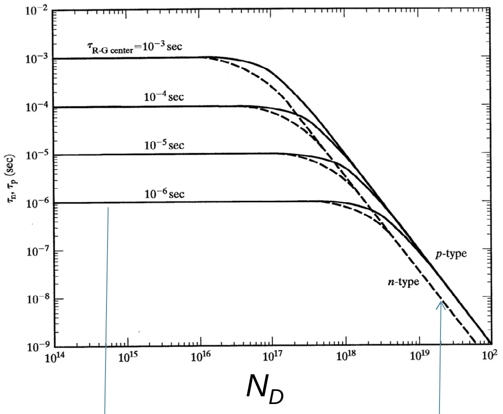
$$R = R_{SRH} + R_{direct} + R_{Auger}$$

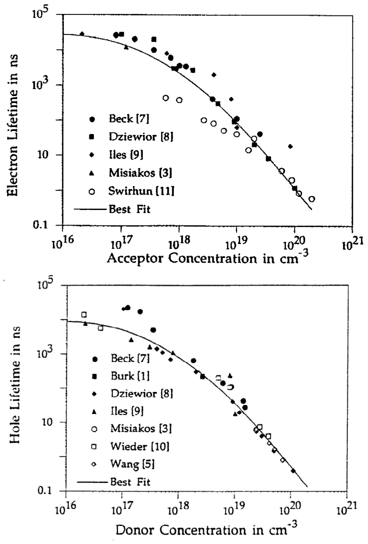
$$= \Delta n\left(\frac{1}{\tau_{SRH}} + \frac{1}{\tau_{direct}} + \frac{1}{\tau_{Auger}}\right)$$

$$= \Delta n\left(c_n N_T + BN_D + c_{n,auger} N_D^2\right)$$

$$\tau_{eff} = \left(c_n N_T + BN_D + c_{n,auger} N_D^2\right)^{-1}$$

Effective Carrier Lifetime with all Processes





$$\tau_{eff} \approx c_{n,auger} N_D^{-2}$$

$$\tau_{eff} = \left(c_n N_T + B N_D + c_{n,auger} N_D^2\right)^{-1}$$

Elec. Dev. Lett., 12(8), 1991.

Conclusion

SRH is an important recombination mechanism in important semiconductors like Si and Ge.

SRH formula is complicated, therefore simplification for special cases are often desired.

Direct band-to-band and Auger recombination can also be described with simple phenomenological formula.

These expressions for recombination events have been widely validated by measurements.