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ECE606: Solid State Devices
Lecture 13: Recombination-Generation

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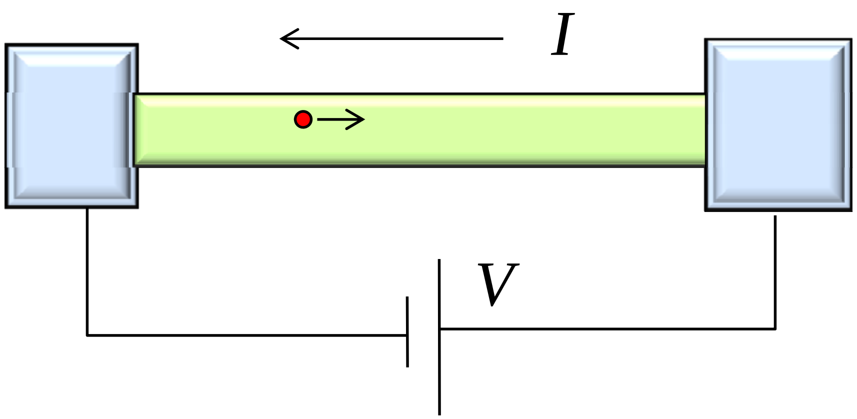
Outline

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 (n)

velocity (v)

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

Quantum Mechanics + Equilibrium Statistical Mechanics

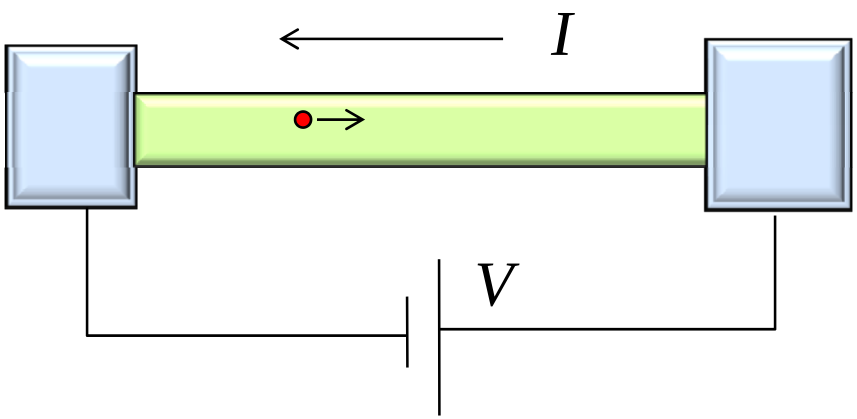
$\Rightarrow$ Encapsulated into concepts of effective masses and occupation factors (Ch. 1-4)

Transport with scattering, non-equilibrium Statistical Mechanics

$\Rightarrow$ Encapsulated into drift-diffusion equation with recombination-generation (Ch. 5 & 6)

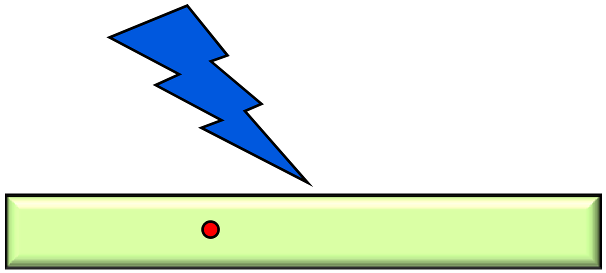
Non-equilibrium Systems

Chapter 6



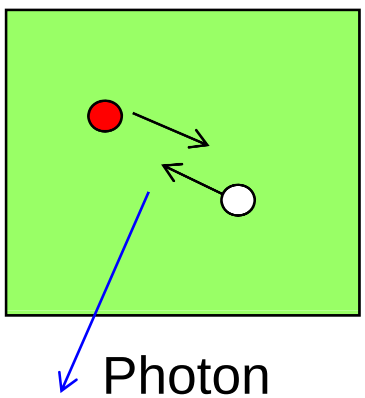
vs.

Chapter 5

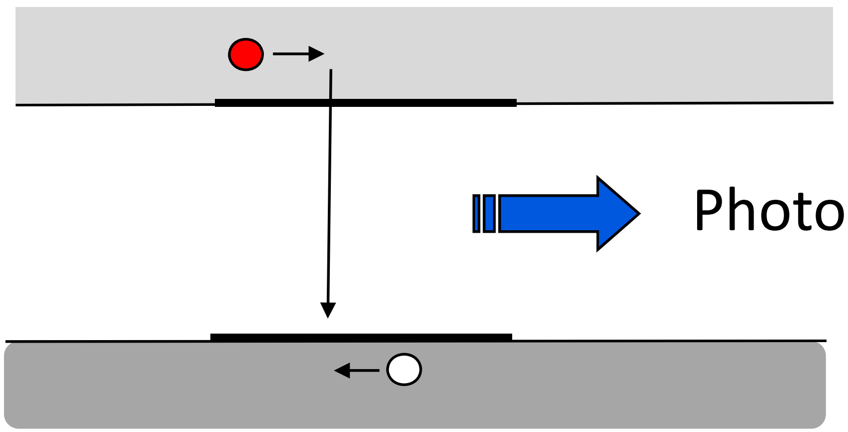


Direct Band-to-band Recombination

In real space …



In energy space …

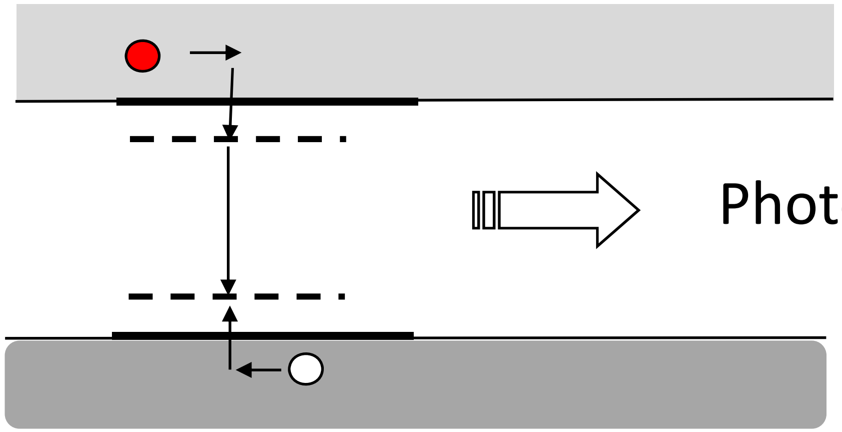


GaAs, InP, InSb (3D)

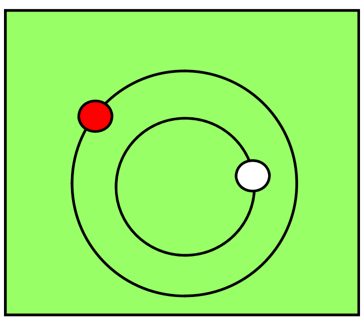
Lasers, LEDs, etc.

Direct Excitonic Recombination

In energy space …



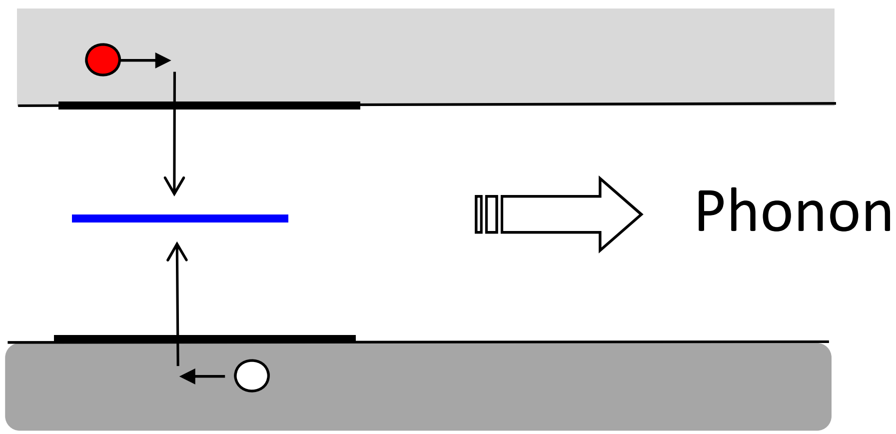
In real space …

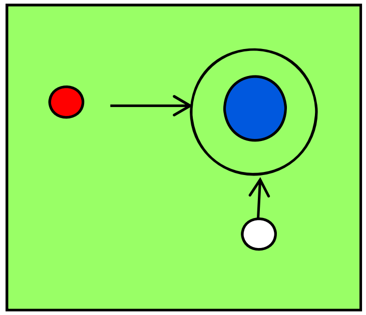


CNT, InP, ID-systems

Transistors, Lasers, Solar cells, etc.

Indirect Recombination (Trap-assisted)

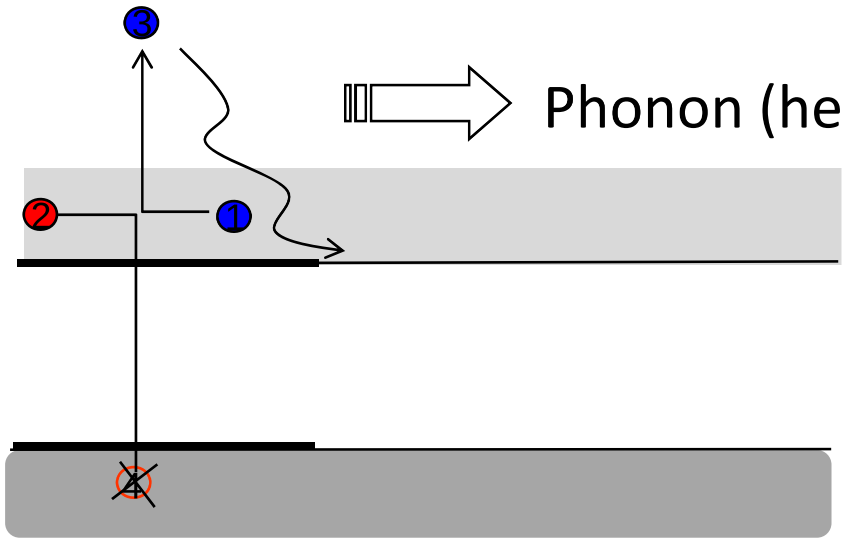




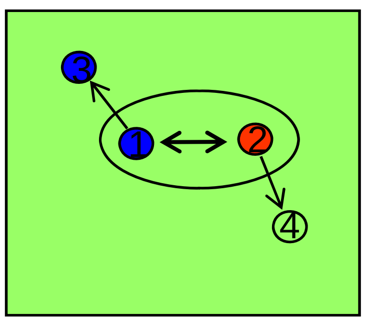
Ge, Si, ...

Transistors, Solar cells, etc.

Auger Recombination



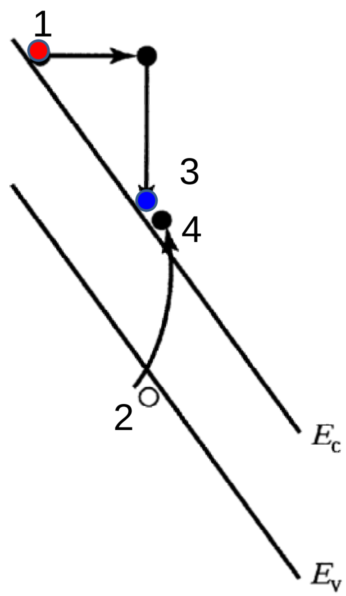
Phonon (heat)

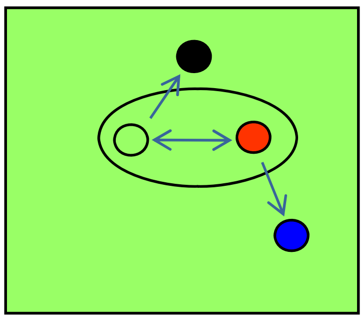


InP, GaAs, …

Lasers, etc.

Impact Ionization – A Generation Mechanism

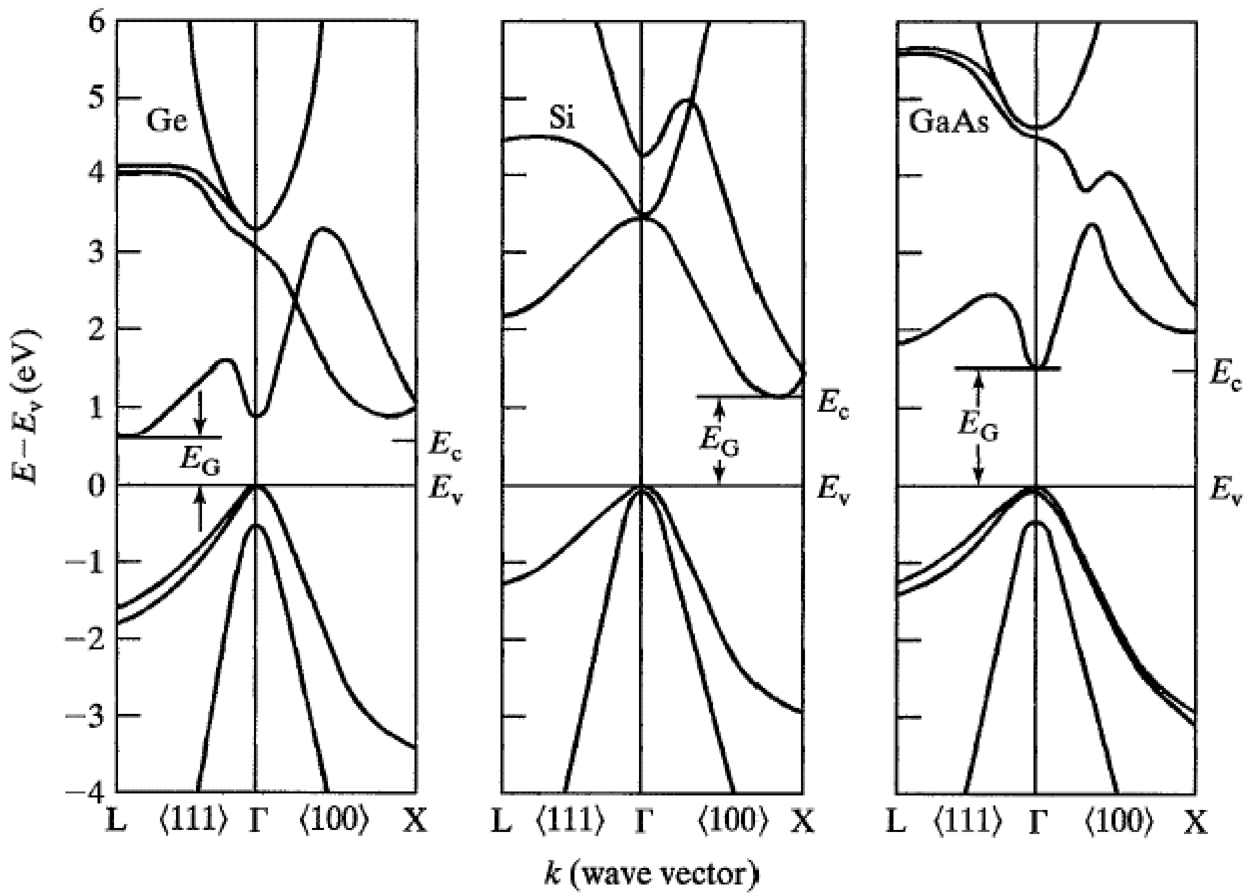




Si, Ge, InP

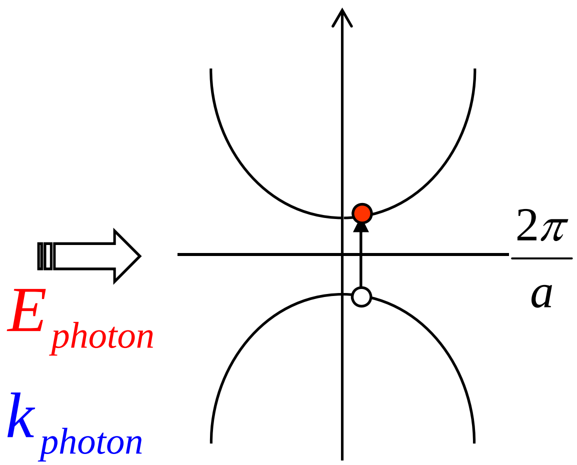
Lasers, Transistors, etc.

Indirect vs. Direct Bandgap



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

Photon Energy and Wavevector



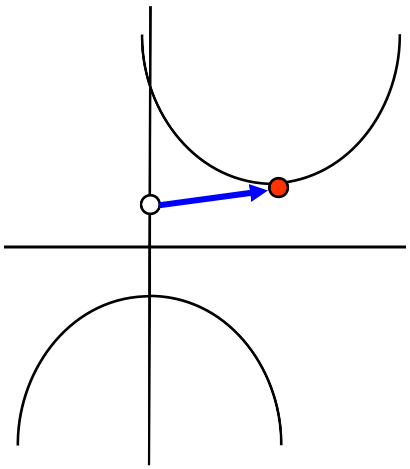
$$E_V + E_{photon} = E_C$$

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

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

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

Phonon Energy and Wavevector



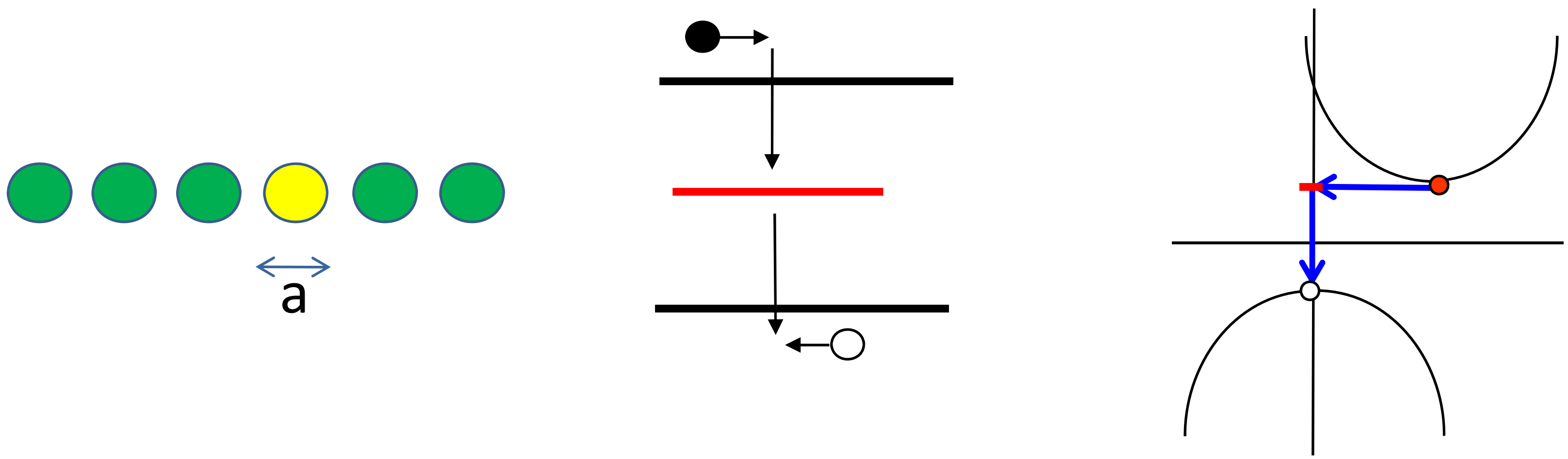
$$E_V + E_{phonon} = E_C$$

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

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

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
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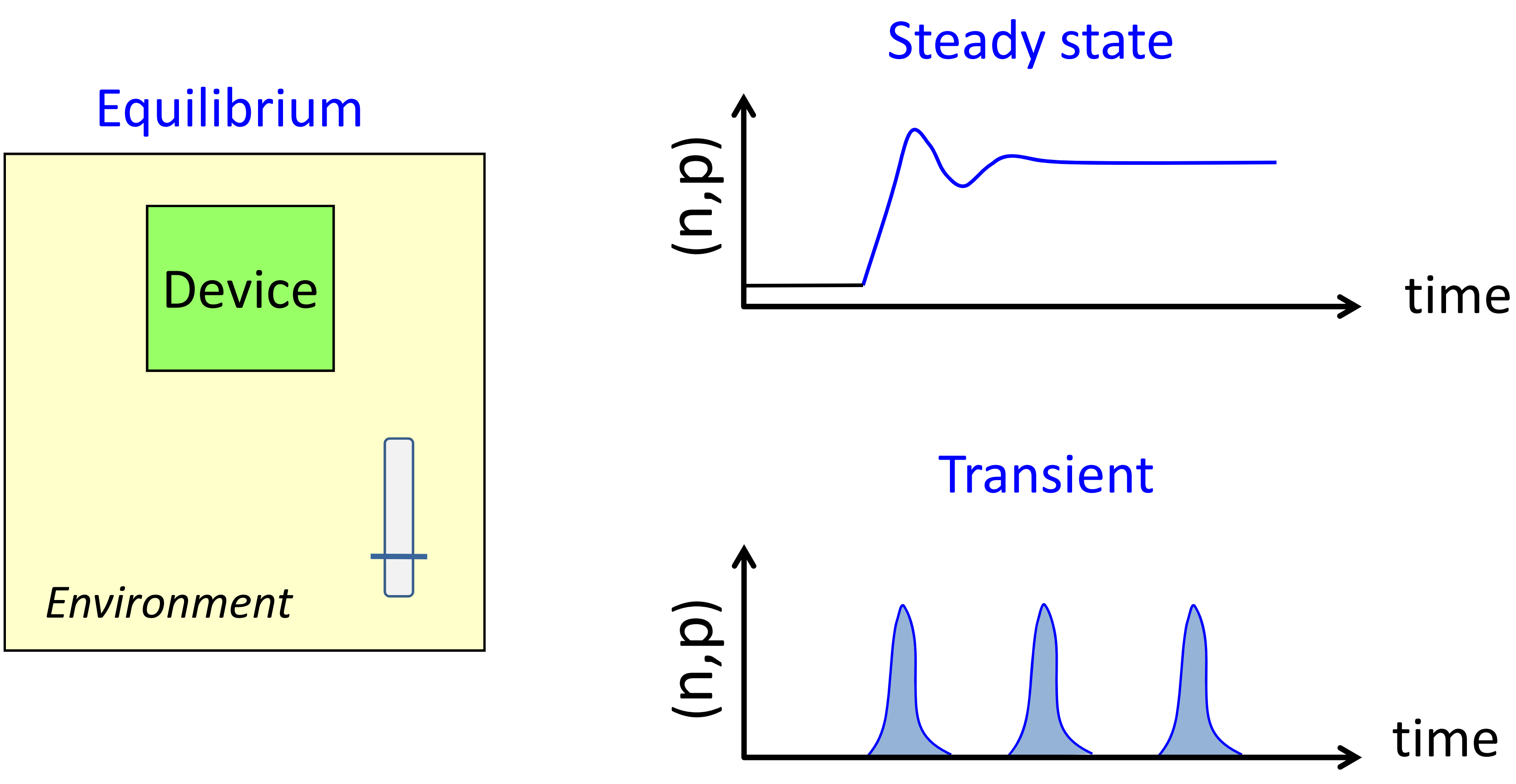
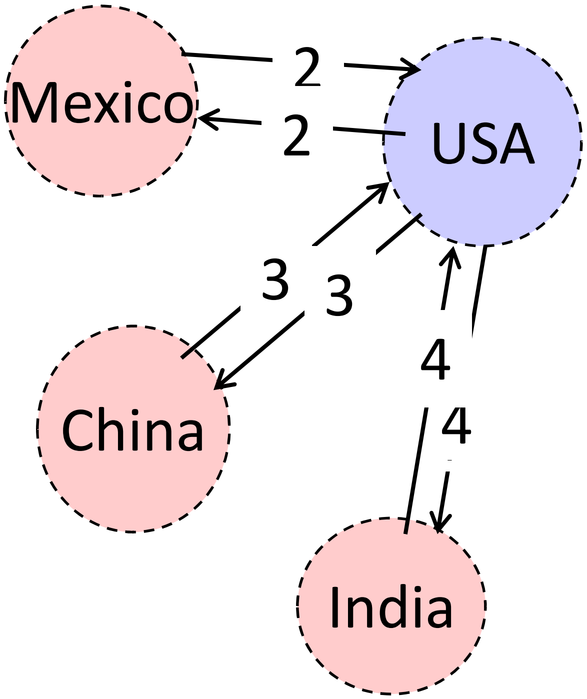
Equilibrium, Steady state, Transient



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.

Steady-state Response

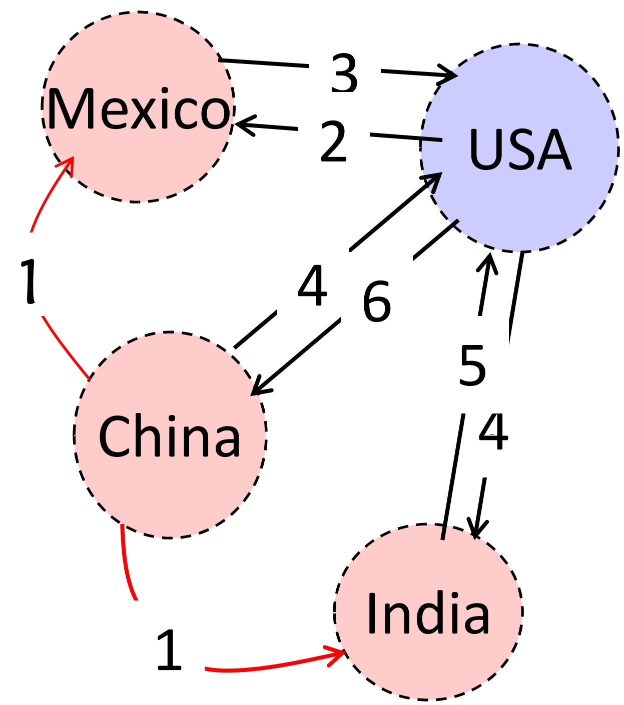
Disturbing the detailed balance requires create non-equilibrium conditions (needs energy). Unidirectional forces (red lines) can create such Non-equilibrium conditions.

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).

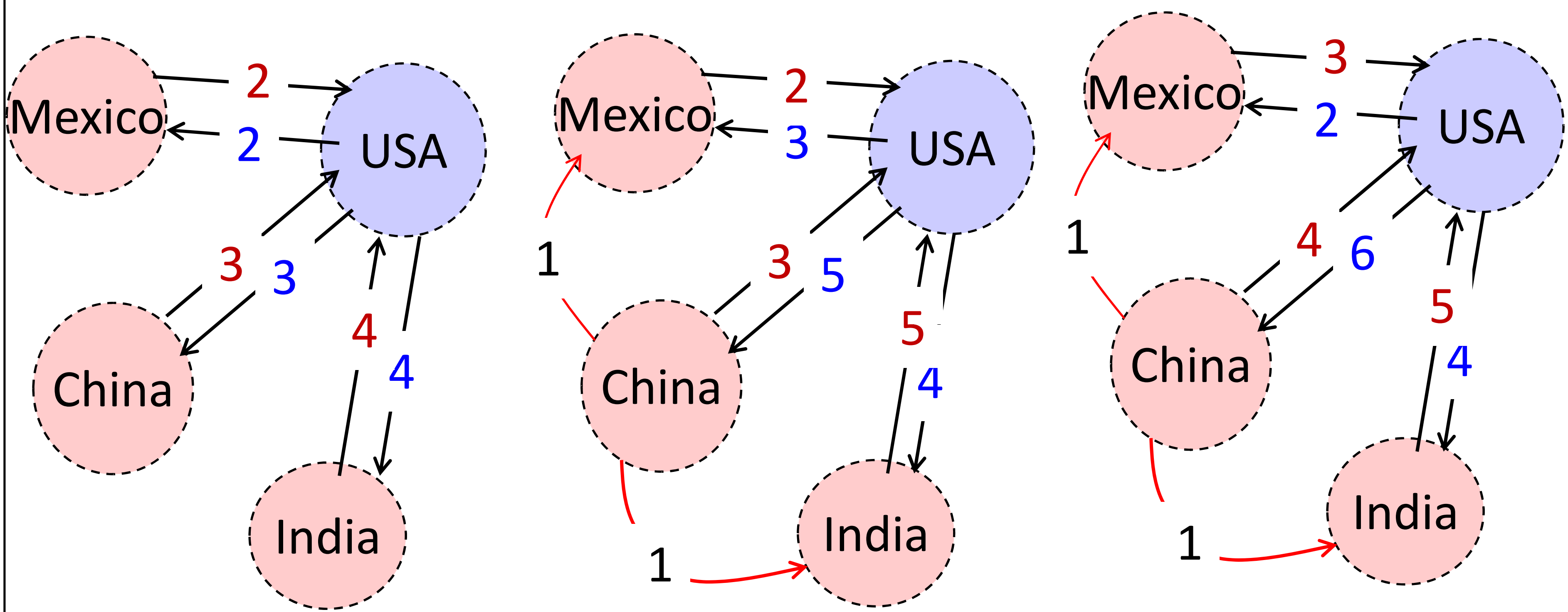
The population of a country (energy level) remains constant with time after steady state is reached.

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

Forced unidirectional connections (red lines) disturbs equilibrium (e.g. 9 in/12 out at time t1 local populations not conserved, but global population is ….

12 in 12 out
Population stabilized

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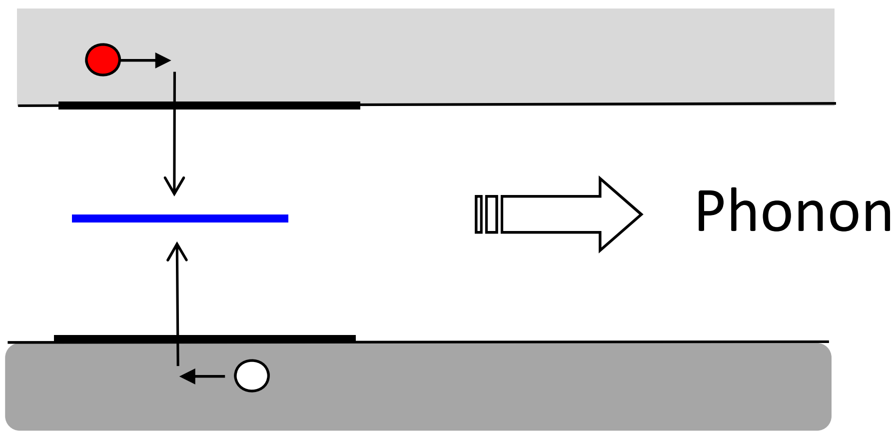
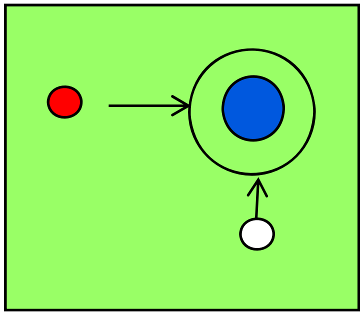
Indirect Recombination (Trap-assisted)





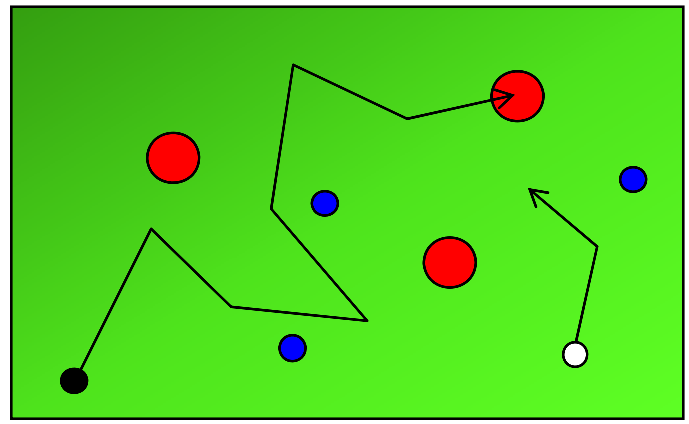
Ge, Si, ...

Transistors, Solar cells, etc.

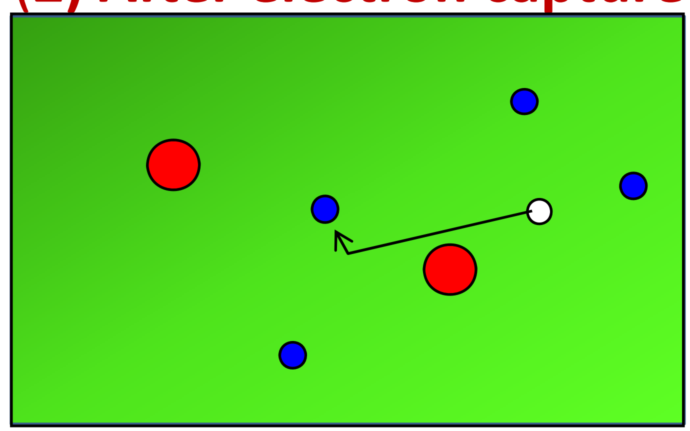
Physical view of Carrier Capture/Recombination

$$N_T = n_T + p_T$$

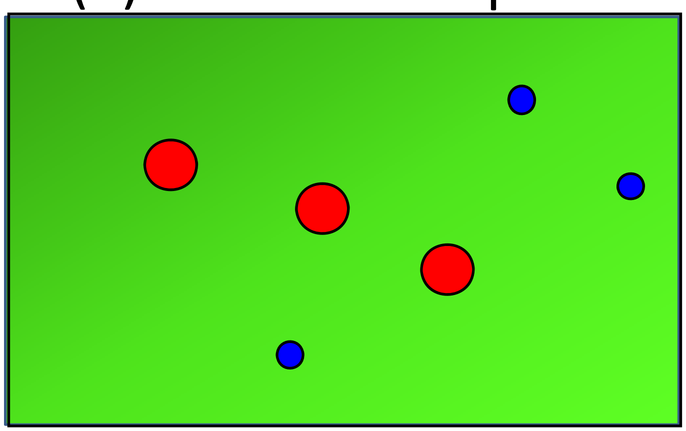
(1) Before a capture



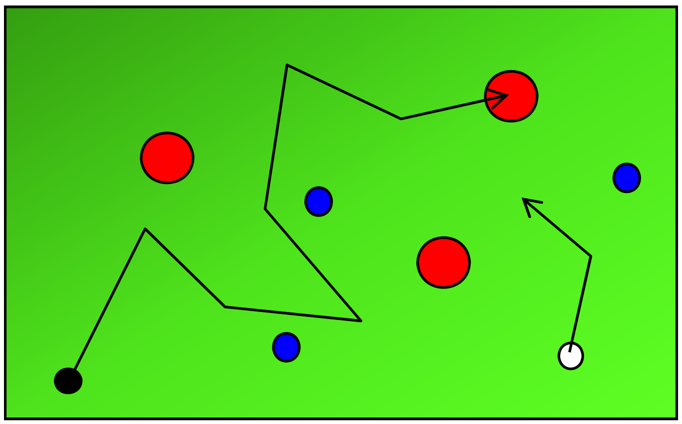
(2) After electron capture

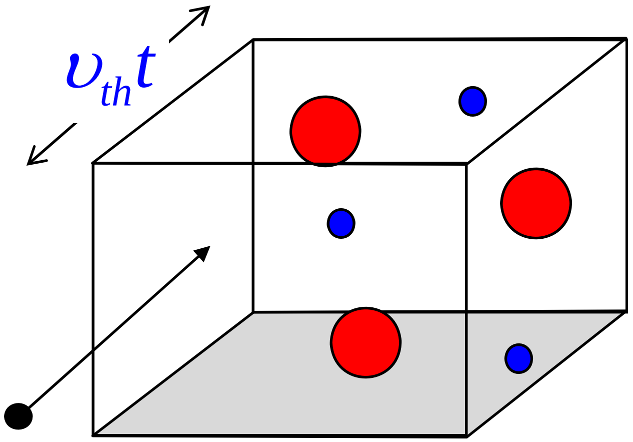


(3) After hole capture



Carrier Capture Coefficients





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

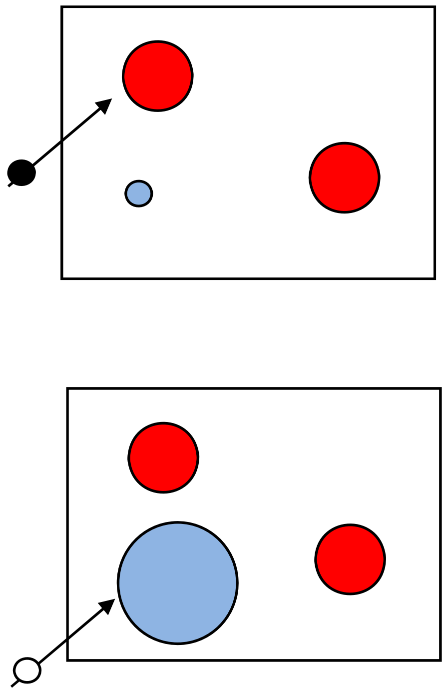
$$\equiv -c_n p_T n \qquad c_n \equiv \sigma_n \upsilon_{th}$$

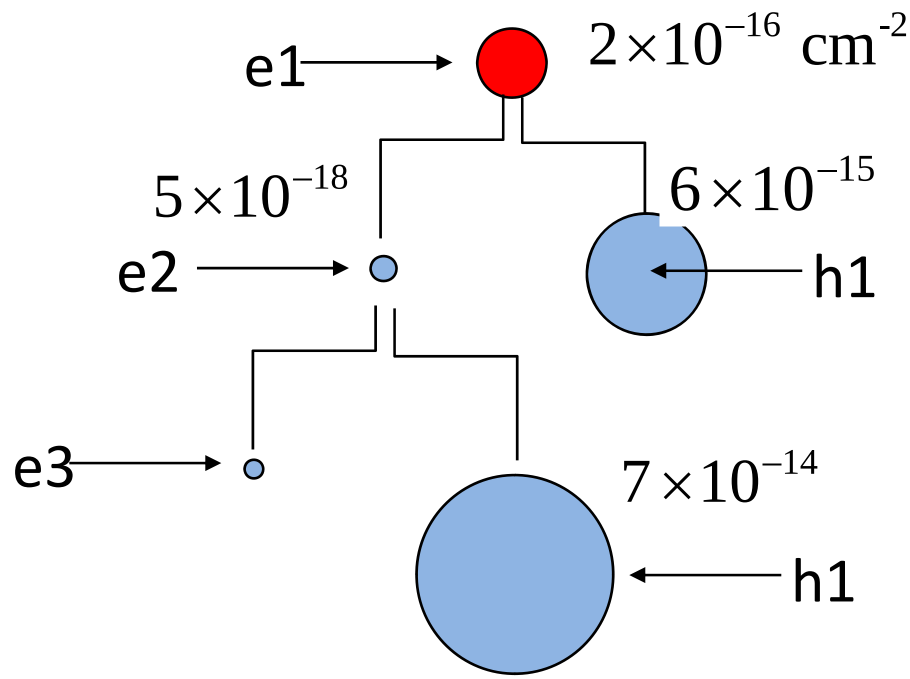
$$\frac{1}{2} m^* \upsilon_{th}^{\ 2} = \frac{3}{2} kT$$

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.